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The ingenuity of common workmen: and the invention of the computer

Byron Paul Mobley
Iowa State University

The ingenuity of common workmen: And the invention of the computer

by

Byron Paul Mobley

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Committee Member

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Committee Member

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Committee Member

Signature was redacted for privacy.

Committee Member

Signature was redacted for privacy.

Major Professor

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For the Major Program

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For the Graduate College

To Donald Ray Mobley, a common workman whose intelligence, industriousness, and integrity have won the admiration of all who have known him

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CHAPTER 1. SMALLER IS BETTER BUT COMPROMISE IS NECESSARY

Prevailing wisdom has it that electronic digital computers exist because governments sponsored their development. Computers have indeed received public backing, but the private sector played a larger role than acknowledged, and moreover, there is considerable evidence that it did not need help to invent computers or take them to market. A history of computers suggests that Adam Smith, the eighteenth-century Scottish philosopher, had it right. He believed that minimal and aloof government best served society, and with that, the inherent genius and diligence of citizens are themselves enough to ensure invention and the general prosperity.

The first modern computer has been widely reputed to be the ENIAC,[1] a machine of such awesome size and complexity that only government, it is believed, could have mustered the initiative and money to create it. The ENIAC weighed thirty tons, occupied a large room, and contained approximately 18,000 vacuum tubes.[2] It cost $750,000, or so, a huge sum at the time.[3] The U.S. Army gave the University of Pennsylvania funding to build the ENIAC for calculating artillery tables during World War II, although the computer was not completed until afterwards. John W. Mauchly and J. Presper Eckert, a physics instructor and an electrical engineering graduate student, respectively, and closely identified with the project, won acclaim as the inventors of the computer.

The federal government continued to support computer projects generously. The financial largess came mostly through defense agencies and resulted in a bewildering number of one-of-a-kind computers, many with playful names, some from acronyms, like ILLIAC, ORDVAC, ORACLE,

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[1] ENIAC is an acronym for Electronic Numerical Integrator and Computer.

[2] Arthur W. Burks, "Electronic Computing Circuits of the ENIAC," *Proceedings of the I.R.E.* 35, no. 8 (August 1947), 756-757. Strictly speaking, the ENIAC contained about 18,000 vacuum tube envelopes, or containers, many with two triodes. Most tubes were in accumulators, the main computational components of the ENIAC. Many of those tubes were of the twin-triode type.

[3] The cost estimate is from Nancy Stern, who has written the most frequently cited account of the ENIAC. See, Stern, *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Bedford, Massachusetts: Digital Press, 1981), 50-51. The figure is from a table entitled, "ENIAC." Saul Rosen, another historian, agreed in a more recent account of the ENIAC. Specifically see, "The Origins of Modern Computing," *Computing Reviews* 31, no. 9 (September 1990), 450. Other estimates on the cost of the ENIAC have gone to $1 million but most are less. Historian Paul Ceruzzi put it at $500,000. See, *The Reckoners: The Prehistory of the Digital Computer, From Relays to the Stored Program Concept* (Westport, Connecticut: Greenwood Press, 1983), 123. See, "Table 5.1. The ENIAC." Herman H. Goldstine, Army liaison to the ENIAC project, cited an exact cost of $486,804.22. See, *The Computer from Pascal to von Neumann* (Princeton, New Jersey: Princeton University Press, 1972), 154, footnote 10. John W. Mauchly also estimated the cost at $500,000. See, "Mauchly on the Trials of Building ENIAC," *IEEE Spectrum* 12, no. 4 (1975), 76. It is likely that no one knew its true cost.

MANIAC, JOHNNIAC, and others.[4] The ENIAC helped inspire this frenetic activity in publicly financed computer building but served only incidentally as a model for any other machine. Nothing like the ENIAC was built again. It was too limited in capabilities, too complex, too difficult to use, and too expensive to be worth replicating. The designs of two other early computers constructed largely under the auspices of the federal government defined the direction computers took. Neither had much in common with the ENIAC, although they had major similarities with one another.

The team building the ENIAC initiated the first of the two truly influential machines that followed. Recognizing serious deficiencies in the yet unfinished ENIAC, Eckert, Mauchly, and others began computer design anew with the EDVAC.[5] Mathematician John von Neumann joined as a consultant in late summer 1944 and the next spring wrote *First Draft of a Report on the EDVAC*. It dealt not with nuts-and-bolts issues as much as it formulated a fundamental theoretical framework for electronic digital computers that continues as their basis to this day. Notable is that von Neumann chose the logic and language of the "logical calculus of the ideas immanent in nervous activity" of biophysicists Walter Pitts and W. S. McCulloch to explain and systematize computer components and circuits. Rather than vacuum tubes and specialized electronics, von Neumann used human organ and neuron analogies to discuss alternative designs and make recommendations. Among the most urgent was that the EDVAC, "should be as simple as possible, that is, contain as few elements as possible."[6] The EDVAC was not completed by the University of Pennsylvania until 1952 and cost an estimated $467,000, with funding again provided by the Army, but it reflected the principles advocated by von Neumann. With a spare design including approximately 3,600 vacuum tubes, the EDVAC handily met goals of being simpler, smaller, and easier to use than the ENIAC.[7]

The EDVAC was also more versatile and powerful. In particular, the EDVAC had stored-program capabilities while the ENIAC did not. Programming the ENIAC entailed resetting a myriad of switches and relocating numerous jumper cables. The physical setup alone could take a couple of days. The EDVAC was programmed in much the same manner as computers today. Instructions and data were fed into the EDVAC, converted to binary code, and stored and manipulated as the instructions commanded. That capability made the EDVAC a computer in the complete sense. A

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[4] The computers specifically mentioned here derived from one particularly influential machine, the IAS computer. As another of those, and a name topper, the University of Sidney completed the SILLIAC in 1956.

[5] EDVAC is an acronym for Electronic Discrete Variable Automatic Computer.

[6] John von Neumann, *First Draft of a Report on the EDVAC*, 1945; reprinted in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks (Cambridge, Massachusetts: MIT Press, 1987), 23-25 and 28-29.

[7] Stern, *From ENIAC to UNIVAC*, 94-95 and 133.

computer as the word means today is automatic, general purpose, and stored program.[8] Besides not having the latter characteristic, the ENIAC was neither automatic nor fully general purpose, and therefore, not a true computer.

Von Neumann defined an automatic computer as one that when given instructions, "must be able to carry them out completely and without any need for further intelligent human intervention."[9] That did not describe the ENIAC. Data—always numbers—entered and left ENIAC as patterns of punched holes in paper cards, except for constants and initial values entered as switch settings. The ENIAC had little internal memory, so its operation required streams of data cards. Not only did initial and final values have to be dealt with manually, so did partial results, because the small memory meant they often could not be stored internally for use in the next steps of an ongoing calculation. Moreover, its miniscule memory limited the range of problems the ENIAC could handle.[10] ENIAC is best defined as an ultra-complex electronic calculator.[11] The EDVAC had a fraction of its physical size but one hundred times the memory.[12] The extra memory was essential to making the EDVAC automatic, general purpose, and stored program. The EDVAC thus gets credit as the first true electronic digital computer by conception.

Another machine, perhaps the EDSAC,[13] deserves the honor of first one built. A product of scientists at Cambridge, England, the EDSAC, finished in May 1949 with funding from Cambridge University and J. Lyons, a food catering company, borrowed the basic design of the EDVAC.[14] Computer historians have speculated that the first completed true computer came in England because

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[8] Fred Gruenberger, "What's In a Name?" *Datamation* 25, no. 5 (1 May 1979), 230.

[9] Von Neumann, *First Draft of a Report on the EDVAC*, 17.

[10] Allan G. Bromley, "What Defines a 'General-Purpose' Computer?" *Annals of the History of Computing* 5, no. 3 (July 1983), 303-305. See also comments by Konrad Zuse and Brian Randell at the end of Arthur W. Burks and Alice R. Burks, "The ENIAC: First General-Purpose Electronic Computer," *Annals of the History of Computing* 3, no. 4 (October 1981), 396-397. For a listing of types of problems the ENIAC solved, see W. Barkley Fritz, "ENIAC—A Problem Solver," *Annals of the History of Computing* 16, no. 1 (1994), 41-45.

[11] No distinction will be made here between calculators and computers in ordinary usage.

[12] Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 377.

[13] EDSAC is an acronym for Electronic Delay Storage Automatic Calculator (not computer).

[14] The first stored-program computer may have been a small, experimental one completed at Manchester, England, in 1948. Dubbed later the "baby Mark I," it had no working value but led the following year to a full-scale version, the Manchester Mark I. S. H. Lavington, "Computer Development at Manchester University," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 433; Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988), 138-141.

scientists there had less money. They focused on getting the job done, unlike in America, where scientists had public money to burn and could afford to be less diligent.[15]

The relationship of Eckert and Mauchly with von Neumann began cordially but deteriorated after *First Draft*, which drew immediate interest. Von Neumann enjoyed a reputation for exceptional genius even before coming to the U.S. from his native Hungary in 1930. His lifetime work in mathematics, physics, economics, and beginning with the EDVAC, computer science is astonishing in its brilliance and scope. His services were in such demand during the war that he shuttled among governmental agencies providing scientific advice. He had an instrumental role in the Manhattan Project promoting the detonation of a plutonium bomb by implosion, for example.[16] In fact, the atomic bomb project pushed von Neumann to search for better computational methods. A chance encounter at a train station with Herman Goldstine, a Ph.D. in mathematics and Army liaison officer to the ENIAC and EDVAC projects, led him to become involved with the two computers.[17]

Von Neumann contributed little of a technical nature to the ENIAC, because its design had already been frozen. Eckert and Mauchly welcomed him, however, because he gave the project credibility. Few scientists who knew of the ENIAC had a favorable opinion.[18] However, von Neumann encouraged colleagues from Los Alamos to give the computer its first problem. Nuclear weapons by then had a higher priority than ballistics. Theoretical physicists Stanley P. Frankel and Nicholas Metropolis thus traveled to Pennsylvania with 1 million paper cards to test a theory by physicist Edward Teller on the feasibility of the hydrogen bomb, or "Super."[19] The ENIAC began the calculations in late 1945 and ran them intermittently over several months. A good solution exceeded the meager capabilities of the ENIAC, but it managed approximations—albeit, "insufficient and inaccurate"—that suggested Teller's theory might be flawed.[20]

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[15] Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York City: BasicBooks, 1996), 99.

[16] William Aspray, *John von Neumann and the Origins of Modern Computing* (Cambridge, Massachusetts: MIT Press, 1990), 28-36.

[17] Goldstine, *The Computer from Pascal to von Neumann*, 182.

[18] Stern, *From ENIAC to UNIVAC*, 72; John G. Brainerd, "Genesis of the ENIAC," *Technology and Culture* 17, no. 3 (July 1976), 488.

[19] Goldstine, *The Computer from Pascal to von Neumann*, 214-215 and 226-227.

[20] Edward Teller quoted in Clark R. Mollenhoff, *Atanasoff: Forgotten Father of the Computer* (Ames, Iowa: Iowa State University Press, 1988), 177; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, Earl R. Larson, "Findings of Fact, Conclusions of Law and Order for Judgment," 19 October 1973, sections 1.1.4.3-1.1.4.17. ISU, Parks, "Henry L. Hanson Papers" (box 5, folders 4-8).

The Army interrupted the calculations in February 1946 to unveil the ENIAC with no sparing of expenses, including a sumptuous five-course dinner featuring lobster bisque and filet mignon.[21] The Army did not disclose how the ENIAC computed, because that information remained classified. However, with the glowing publicity touting it as an "electronic brain,"[22] and the reputation of von Neumann behind it, the ENIAC won accolades, although still not from scientists in the know.[23] As for Teller, he helped develop another hydrogen bomb theory that worked.[24]

Eckert and Mauchly gained stature from their association with von Neumann, and his participation in design of the EDVAC provided welcomed inducement for the Army to fund its construction. However, when not cited in *First Draft*, Eckert and Mauchly became resentful. The two men considered themselves sole inventors of the EDVAC, and it infuriated them not to get credit. To make matters worse, Eckert and Mauchly had hoped to patent the EDVAC, but copies of *First Draft* put descriptions of much of its technology into the public domain too soon for them to meet the deadline for filing an application.[25] Patent law stipulated a filing must occur no later than one year from a public disclosure. Von Neumann's paper constituted a disclosure, even if unintentional, and Eckert and Mauchly waited too long after its distribution to apply. They did patent features not detailed in the report, but those patents were all invalidated later for other reasons.

The EDVAC was not solely, or mainly, Eckert and Mauchly's invention, but historians agree that von Neumann should have cited them and others in *First Draft*. Goldstine concurred in that opinion but nonetheless found von Neumann the only "indispensable" participant in the design of the

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[21] Scott McCartney, *ENIAC: The Triumphs and Tragedies of the World's First Computer* (New York: Walker and Company, 1999), 106.
[22] Quoted in Campbell-Kelly and Aspray, *Computer*, 98.
[23] With the publicity, the University of Pennsylvania came under pressure to explain the ENIAC. The school therefore presented an eight-week computer course in summer 1946, after the electronic marvel had been declassified apparently. A number of students expected the ENIAC to be the main topic, but although it was the only commonly known electronic digital computer at the time, dedicated discussion was completely absent from the syllabus. The school preferred topics relating to the EDVAC and other advanced ideas, in particular numerical methods, which deal with how computers perform mathematics. For instance, one lecturer spoke of a machine under design at the Naval Ordnance Laboratory. The NOL computer was probably the most sophisticated computer at the time but never completed. On the other hand, another lecture went to the ASCC, an electromechanical computer completed before the ENIAC. Students complained about the absence of information on the ENIAC but were told, "Its (the ENIAC) no good, so why talk about it." The school eventually relented and included lectures on the ENIAC. Martin Campbell-Kelly and Michael R. Williams, eds., *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers* (Cambridge, Massachusetts: MIT Press, 1985), xiv-xv and 490.
[24] Ceruzzi, *The Reckoners*, 127.
[25] Stern, *From ENIAC to UNIVAC*, 72 and 96-97.

EDVAC. He pointed out that von Neumann had not intended for *First Draft* to be copied widely. It did not get published formally until long after his untimely death from cancer in 1957. Indeed, brilliant though the report was, von Neumann never completed it. He left gaps of information throughout. And although he did not cite others in *First Draft*, von Neumann otherwise selflessly attributed the EDVAC to a team effort.[26] However, he rightfully considered himself responsible for some ideas and tried to patent features of the EDVAC using *First Draft* as evidence. [27] His attempt failed for the same reason that Eckert and Mauchly could not apply. Had either von Neumann or Eckert and Mauchly submitted on time, an acrimonious legal battle would likely have ensued.[28]

Disheartening though the situation over the EDVAC must have been for both parties, neither had time to dwell on it. Eckert and Mauchly and von Neumann had already turned their attentions to other projects they separately had underway. Many people associated with the EDVAC left to follow one or other of the two parties, which was another reason why it took the University of Pennsylvania so long to finish it.

In the case of von Neumann, he searched for funding to build a more advanced computer. He made the issue more troublesome by demanding potential sources impose few restrictions on how the computer be used. He had in mind a strictly scientific computer capable of solving large sets of linear algebraic equations and partial differential equations, especially non-linear ones. Such equations had been largely ignored because of the near impossibility of finding solutions using standard methods, but they represent much of the phenomena of the universe in hydrodynamics, quantum theory, aerodynamics, and other breaking areas of interest.

Von Neumann avoided asking industry for help because he believed it, "would be influenced by its own past procedures and routines, and . . . not be able to make as fresh a start as desirable."[29]

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[26] Campbell-Kelly and Aspray, *Computer*, 96.

[27] According to Herman Goldstine, in design of the EDVAC, "Eckert and Mauchly unquestionably led on the technological side and von Neumann on the logical." Von Neumann believed himself specifically responsible for the programming code, serial architecture, and use of a cathode ray tube as memory. The latter found use in certain computers after the EDVAC. Goldstine, *The Computer from Pascal to von Neumann*, 196-198 and 224. Eckert specified what he believed to be his and Mauchly's contributions in J. Presper Eckert, "The ENIAC," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 530-535; Aspray, *John von Neumann and the Origins of Modern Computing*, 43.

[28] Stern, *From ENIAC to UNIVAC*, 96-97.

[29] Von Neumann to Frank Aydelotte, director of the Institute for Advanced Study, memorandum, 5 September 1945. Quoted in Aspray, *John von Neumann and the Origins of Modern Computing*, 54.

Even so, he allowed the Radio Corporation of America (RCA) to spend $100,000 developing a new type of memory, with resulting patents as its compensation. Much of the rest of the funding he received from the military by promising that problems the computer solved could have defense ramifications. Moreover, he suggested that the military should save money overall by building additional computers based on the one he planned. The other computers could be directly applied to military interests, including substituting for physical testing. For example, he claimed that computerized models could substitute for up to 75 percent of the work done in wind tunnels but cost less. Von Neumann thus procured funding from the Army, Navy, and later, the Atomic Energy Commission. In late 1945, he began development at the Institute for Advanced Study (IAS) at Princeton, where he had been associated before the war, and which added another $100,000 to his funding.[30] The design of the IAS computer used that of the EDVAC as a starting point, but von Neumann relaxed his gospel of simplicity espoused in *First Draft* and made changes that complicated its architecture to improve its performance.

Computer architecture is a concept that emerged later, but among other things, refers to how components of a computer are organized.[31] The ENIAC, EDVAC, and IAS computer represented the range of architectures. The ENIAC had a parallel architecture, which meant it could perform multiple computations simultaneously. For example, the ENIAC could at any given instant be adding several separate number sets. Furthermore, the ENIAC calculated with all digits in those number sets simultaneously. This ability to perform operations in parallel with multiple number sets and all their digits made the ENIAC an architectural extreme. The EDVAC represented the other extreme. Computers that calculate by one operation at a time have a serial or, as it is usually called, sequential architecture. Humans consciously solve problems sequentially, so it is not surprising that von Neumann was predisposed to give the EDVAC a serial architecture.[32] Parallel architecture has the promise of advantage in overall speed of computations but in practice has not worked well. Programming a parallel computer is generally much more difficult than a serial machine. In fact, the

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[30] Aspray, *John von Neumann and the Origins of Modern Computing*, 49-61; George Stibitz, "Introduction to the Course on Electronic Digital Computers," 8 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 15.
[31] Richard E. Smith, "A Historical Overview of Computer Architecture," *Annals of the History of Computing* 10, no. 4 (1989), 277.
[32] Von Neumann was well aware that the brain is much more complex than a sequential computer. He though the brain might actually operate more like a parallel computer. See Aspray, *John von Neumann and the Origins of Modern Computing*, 206-209.

operators of the ENIAC modified it to compute sequentially after a few months attempting to program it in its original form.[33]

By contrast, the IAS computer had a mixed architecture. Like the EDVAC, the IAS computer dealt with one number set at a time, or serially. Like the ENIAC, the IAS computer calculated with all digits in that set in parallel, at forty binary digits per number. The IAS computer represented a compromise, but a highly satisfactory one. With Julian Bigelow as chief engineer through most of its development, the IAS computer was finished in 1951. It cost approximately $650,000,[34] used about 2,600 vacuum tubes, and needed less hardware overall than the EDVAC but paradoxically was at least five times faster.[35] The design of the IAS computer thus improved on the EDVAC, which had improved markedly on the ENIAC. A comparison of these three early machines demonstrates principles still considered basic to design of computers: "smaller is faster," and "good design demands compromise."[36]

Papers published jointly by von Neumann, Goldstine, and Arthur Burks built on *First Draft* to describe the theory behind the IAS computer and define what became known as the von Neumann architecture. If von Neumann was the guiding genius, the other two men had eminent qualifications for computer design. Besides duties as Army liaison, Goldstine had contributed technically to the ENIAC and EDVAC projects, particularly in programming. Burks had been a principal designer of both computers before following von Neumann to Princeton to help with the IAS computer. As

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[33] Fritz, "ENIAC—A Problem Solver," 25. Fritz worked with the ENIAC through much of its history, so he knew its architecture. In describing the ENIAC as a sequential computer, he probably meant that it had been modified to perform computation with numbers serially, and that its ability to compute with digits in parallel remained unchanged. See, for example, Ceruzzi, *The Reckoners*, 147. The purpose of the modification to the ENIAC was to make it a stored-program computer. This upgrade was completed by fall 1948, which made the modified ENIAC one of the first stored-program computers. The change also slowed down the ENIAC by a factor of six to nine. See Fritz, "ENIAC—A Problem Solver," 31-33.

[34] Kent C. Redmond and Thomas M. Smith, *Project Whirlwind: The History of a Pioneer Computer* (Bedford, Massachusetts: Digital Press, 1980), 166.

[35] Goldstine, *The Computer from Pascal to von Neumann*, 263; Julian Bigelow, "Computer Development at the Institute for Advanced Study," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 307; Aspray, *John von Neumann and the Origins of Modern Computing*, 87. See, "Table 4.1 Specifications of the IAS computer"; Aspray reports in another source that the IAS computer had 2,300 vacuum tubes. See, "The Mathematical Reception of the Modern Computer: John von Neumann and the Institute for Advanced Study Computer," in *Studies in the History of Mathematics*, ed. Esther R. Phillips, *Studies in Mathematics* (Mathematical Association of America, 1987), Vol. 26, 177.

[36] David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware / Software Interface* (San Francisco: Morgan Kaufmann, 1994), 97-105 and 149.

Goldstine suggested later without exaggeration, the papers the men co-authored provided nothing less than "the blueprint for the modern computer."[37] The vast majority of computers continue to use variations of the von Neumann architecture. *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, published in June 1946, dealt with the hardware design of the IAS computer. *Planning and Coding Problems for an Electronic Computing Instrument* provided a formal foundation for programming. The second paper was written without Burks and published in several parts in 1947 and 1948.[38]

The von Neumann architecture divides a computer into distinct input, output, logic and arithmetical processing, control, and memory units, or as von Neumann put it, organs. A von Neumann machine solves problems and makes conditional decisions using switching or combinational (computer) logic.[39] It executes instructions sequentially but stores and retrieves bits of information in parallel. Data and instructions are both expressed internally in binary form and handled in identical fashion by both the memory and processing units.[40] The ramification is that a computer is able to modify instructions in the same way data are modified and can use programs to build other programs.[41] This allowed eventually the creation of special programs called compilers to translate high-level computer languages that are easy for humans to grasp to more abstruse assembly language. Other programs called assemblers are used in turn to translate assembly language to the zeros and ones of machine language that a binary digital computer understands directly, although each early binary computer used a unique version of machine language.

Von Neumann created a code of a few simple instructions for the EDVAC.[42] He used his code to write a "sort and merge routine" that probably constituted the first program for a stored-program computer and intended as an experiment in conditional logic.[43] Coding for von Neumann meant binary code; he did not help develop higher languages and cared nothing about them. He used

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[37] Goldstine, *The Computer from Pascal to von Neumann*, 255-256.

[38] The papers are reprinted in full in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks.

[39] Paul Ceruzzi, "Crossing the Divide: Architectural Issues and the Emergence of the Stored Program Computer, 1935-1955," *Annals of the History of Computing* 19, no. 1 (1997), 6.

[40] William Aspray, "The Stored Program Concept," *IEEE Spectrum* 27, no. 9 (September 1990), 51.

[41] According to historian of computers Allan G. Bromley, the idea of using programs to build other programs perhaps should be attributed to Maurice Wilkes and D. J. Wheeler as part of their work building the EDSAC at Cambridge in England. Bromley, "What Defines a 'General-Purpose' Computer?" 305.

[42] Von Neumann, *First Draft of a Report on the EDVAC*, 76-82.

[43] Donald E. Knuth, "Von Neumann's First Computer Program," reprinted in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks (Cambridge, Massachusetts: MIT Press, 1987), 83-96.

code to the extent that he did, not to make programming easier, but to use memory more efficiently.[44] The IAS computer was thus programmed in machine language, an annoyance posing no particular obstacle to von Neumann, legendary for his ability to do complex calculations in his head.[45] Scientists from Los Alamos got first use of the IAS computer, like for the ENIAC, for calculations related to development of hydrogen bombs.

After the discouraging battle with Eckert and Mauchly over the EDVAC patent rights, von Neumann insisted that all new concepts emanating from the IAS computer be placed into the public domain.[46] There is no evidence that von Neumann ever sought undue personal benefit from his work with computers. It is likely that he had attempted to patent parts of the EDVAC to ensure the general availability of the technology and not for profit.

As another aside, the main exceptions to computers based on the von Neumann architecture are supercomputers, which are highly parallel machines. Supercomputers might thus be thought to follow the ENIAC. However, supercomputers actually have architectures more closely related to von Neumann machines except they have multiple processors.

While von Neumann concerned himself with the IAS computer and a variety of other weighty intellectual endeavors, Eckert and Mauchly also continued to develop computers. They resigned, or were fired—it is not clear which—from the University of Pennsylvania in March 1946 in a dispute over ownership of patents. Von Neumann attempted to hire Eckert as chief engineer for the IAS computer but rescinded his offer. International Business Machines (IBM) proposed to fund a computing laboratory for Eckert and Mauchly. The men turned the proposition down, deciding instead to form a business manufacturing and selling computers.[47] That venture is regarded as the pioneering transition of the computer to the commercial market.

Eckert and Mauchly knew the Census Bureau intended to acquire a computer and had a budget of $300,000, with money coming from the Army through the National Bureau of Standards. The two men estimated that a suitable computer could take at least $400,000 to build. They nevertheless formed a partnership, submitted a bid as the Electronic Control Company (ECC) for the amount available to the Census Bureau, and won the contract. Another bidder was Raytheon

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[44] Paul Ceruzzi, "An Unforeseen Revolution: Computers and Expectations, 1935-1985," in *Imagining Tomorrow: History, Technology, and the American Future*, ed. Joseph J. Corn (Cambridge, Massachusetts: MIT Press, 1986), 198-199.
[45] Bigelow, "Computer Development at the Institute for Advanced Study," 309-310.
[46] Aspray, *John von Neumann and the Origins of Modern Computing*, 45 and 85.
[47] Stern, *From ENIAC to UNIVAC*, 91-92.

Corporation, which presented a realistic bid. Raytheon went on to build the Hurricane computer, also known as the RAYDAC, for the Navy for an estimated $460,000.[48] Eckert and Mauchly took a calculated risk that they could recoup the initial loss by selling additional computers. However, their bid set an unfortunate precedent. They found themselves time and again in desperation selling computers at ruinously low prices to generate enough cash flow to temporarily forestall insolvency.

ECC made its second sale in October 1947. The fledgling partnership struggled financially from its onset, because the Census Bureau agreed to pay for its computer only in stages with completion of corresponding work. Needing money, Eckert and Mauchly contracted to build the BINAC[49] for the Northrop Aircraft Company. The ultimate user was to be the Air Force, which wanted a small, reliable computer to operate onboard an aircraft. The contract had a May 1948 delivery and $100,000 price. The enticement to Eckert and Mauchly was that Northrop paid $80,000 up front. The BINAC finally got delivered in September 1949 at a cost of $278,000. Worse, it did not work, at least not after being shipped across the country. The BINAC could not be taken airborne, but Northrop eventually got some use of it on the ground and paid the remainder of the contractual price. Eckert and Mauchly had to absorb the cost overrun.

The BINAC has historical interest as one of the first true computers completed (loosely speaking) in the United States.[50] A notable feature was use of plastic magnetic tape to move data in and out of the computer more efficiently than with punched cards. The BINAC, with 1,400 vacuum tubes, was essentially two, modified, small-scale EDVACs linked together and likely had good commercial prospects, never mind its poor performance. Mauchly investigated and found a number of universities and businesses interested in buying copies. Despite its advanced state of development, however, Eckert and Mauchly abandoned the design of the BINAC in favor of that of the UNIVAC,[51] the much larger computer on the drawing board for the Census Bureau.

The UNIVAC, too, started with the design of the EDVAC. With 5,400 vacuum tubes,[52] the UNIVAC was bigger in part because of its use of a less efficient, hybrid number system. Where the

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[48] Redmond and Smith, *Project Whirlwind*, 166; Saul Rosen, "Electronic Computers: A Historical Survey," *Computing Surveys* 1, no. 1 (March 1969), 15.
[49] BINAC is an acronym for Binary Automatic Computer.
[50] Given that the BINAC apparently never did work satisfactorily, some historians of computers consider the first stored-program computer in the United States to have been the Standards Eastern Automatic Computer (SEAC), built by the National Bureau of Standards and completed in 1950. Also notable about SEAC was its use of germanium diodes to replace many vacuum tubes. Solid state diodes thereafter became common in computers. Flamm, *Creating the Computer*, 15-16 and 70.
[51] UNIVAC is an acronym for Universal Automatic Computer.
[52] Stern, *From ENIAC to UNIVAC*, 133. See the table entitled, "A Comparison of Architecture, Performance, and Physical Characteristics of the Eckert-Mauchly Computers."

EDVAC and BINAC were binary machines and the ENIAC decimal, the UNIVAC calculated in binary-coded decimal arithmetic.[53] Decimal was believed superior for accounting-oriented computers,[54] and Eckert and Mauchly designed the UNIVAC with businesses in mind. A customer bought a UNIVAC system, including computer and choices of peripheral equipment. Among these were input and output devices using metallic magnetic tape—plastic tape proved yet too flimsy.

Magnetic storage proved key to the success of computers for processing information for businesses. Calculations in business applications are usually rudimentary, although that makes no difference to a digital computer, which cannot tell the difference between bookkeeping and calculus. For all its sophistication, the only operations a digital computer actually does are the most elementary kind. As far as there was a difference in hardware requirements between scientific and business applications, it was assumed the former needed greater precision and the latter needed to handle larger volumes of data as input and output.[55] Thus, performing calculations in decimal avoided the conversions necessary for binary arithmetic. Differences in applications were otherwise in programming. A business computer had to read large amounts of data; manipulate, sort, and rearrange it as desired; and record results, all done accurately.

Eckert and Mauchly did not intend originally to include punched-card equipment with the UNIVAC, because of IBM's domination of such equipment and because of the difficulties in perfecting it. However, when an early customer insisted that card-to-tape and tape-to-card converters be provided, they developed them. Businesses performed accounting functions on electromechanical punched-card equipment, and the availability of the converters explains much of UNIVAC's ultimate success by easing transition to the new computer and tape-storage technologies. Eckert and Mauchly were prescient in recognizing the great market for computers lie not in scientific computing but in information processing for government and business. Of course, their initial contract with the Census Bureau pushed them in that direction. Moreover, a long tradition in business applications already existed for digital calculating machines.

Prescient or not, sales of the UNIVAC only trickled in even at give-away prices. That greater sales did not result probably reflected less a reluctance of businesses to buy computers than more a

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[53] Alice R. Burks and Arthur W. Burks, *The First Electronic Computer: The Atanasoff Story* (Ann Arbor, Michigan: University of Michigan Press, 1988), 276.

[54] Charles J. Bashe, et al., *IBM's Early Computers* (Cambridge, Massachusetts: MIT Press, 1986), 439.

[55] Rosen, "Electronic Computers," 14; Bashe, et al., *IBM's Early Computers*, 115. Beyond the explanation given, business applications involved standardized and periodic operations, and both input and output had to be kept for reference. On the other hand, engineering and scientific applications tended to be individualistic and *ad hoc*. Records were discretionary.

concern with the dismal financial state of the Eckert-Mauchly enterprise. Prudential Insurance Company contracted to buy a system for $150,000, including twenty pieces of peripheral equipment. Eckert and Mauchly offered to sell the A. C. Nielsen Company a system for $100,000. Not only were these prices far too low to cover costs, but the men also promised impossibly close delivery dates. They incorporated in December 1947 to obtain more operating funds. As the Eckert-Mauchly Computer Corporation (EMCC), they gained temporary respite when American Totalisator Company,[56] which had interest in computers for pari-mutuel betting, moved to purchase 40 percent of the voting common stock and loaned money in the interim until the sale went through. Circumstances within American Totalisator then caused it to withdraw. Probably nothing could have saved EMCC in any case, and Eckert and Mauchly sold their company to Remington Rand in 1950.[57]

Remington Rand may have wondered if it had made a smart purchase. EMCC had contracted for six UNIVAC systems for $1.2 million total. Estimated average deliver cost was $500,000 each. Remington Rand placed Leslie Groves, former Army general who headed the Manhattan Project, in charge, retained Eckert as chief engineer, and eventually relegated Mauchly to sales. The company could not break its government contracts, but bullied firms with orders into canceling them by threatening nuisance lawsuits. It shipped the first UNIVAC to the Census Bureau in March 1951 and sold additional ones for about $1 million each. Selling became easier with a publicity windfall when a television network used early return statistics and a UNIVAC to predict Dwight D. Eisenhower 1952 presidential election winner. UNIVAC became synonymous with computer for some time, and the original model was an outstanding machine for its day. Total sales reached forty-six and might have been more if Remington Rand had greater manufacturing capacity. As it were, the initial UNIVAC line never returned a profit.[58] It fell to IBM to make computers commonplace.

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[56] Australian G. A. Julius invented the totalisator for keeping track automatically of bets on racehorses. His entirely mechanical machine was first used in 1913. Subsequent totalisators contained electromechanical telephone switching components and became quite sophisticated. It was therefore natural for American Totalisator Company to be interested in computers. See Randell, ed., *The Origins of Digital Computers*, 241-242.

[57] According to Mauchly, he and Eckert sold their interests in EMCC, including patent rights, to Remington Rand for "$200,000 or $250,000" each. Mauchly quoted in John Costello, "He Changed the World," *The Washingtonian* (December 1983), 96 and 98.

[58] Stern, *From ENIAC to UNIVAC*, 105-159; The selling price for a UNIVAC system comes from a corporate brochure by J. H. Rand entitled, "Remington Rand Progress in the Field of Electronics for Business, Industry and Government," 4 February 1955, 22. A copy is contained in ISU, Parks, "John Vincent Atanasoff Papers" (box 49, folder entitled "Sperry Rand Corporation v. Control Data Corporation"); Campbell-Kelly and Aspray, *Computer*, 125.

The EDVAC and, more directly, the IAS computer furnished the basic pattern for subsequent computers. Remington Rand, IBM, National Cash Register (NCR), and Burroughs, all established manufacturers of data-handling machines, began building commercial computers by the mid-1950s. General Electric (GE), RCA, Philco, Honeywell, and other companies also started producing commercial machines. New corporations, such as Control Data and Digital Equipment Corporation (DEC), were created by end of the 1950s specifically for manufacturing computers.

However, the computer industry became economically significant only after a great more development beyond that manifested by the UNIVAC or IAS computer. A good share of that development came accompanied by government support. Kenneth Flamm, a researcher at the Brookings Institution, studied government funding of computer technology and the rise of the industry. He found that of twenty-five principal innovations in computer-related technologies between 1946 and 1965, all but seven received money from a government to cover some costs of development. Furthermore, first sales of nineteen of the innovations were to a government. This was normally the Federal Government of the United States, but the British Government also invested heavily in computers and related research in the early years. Actual research and development tended to be by universities or corporations.[59] Flamm argued convincingly that the most crucial of the twenty-five inventions were transistors, integrated circuits, rotating magnetic storage, and magnetic core memory. These four technologies proved essential for computers to become widely used, and all involved government funding.[60]

Speed of operation and size of memory are often cited to indicate the performance potential of a computer. Actual performance depends also on architecture and other design attributes that fit together in complex relationship. The best measurement of performance is thus job completion time and is application specific.[61] Vacuum tubes could operate quite fast: The clock rate on the ENIAC averaged 100,000; the EDVAC, 1 million; and the BINAC, 2.5 million pulses per second.[62] Despite its faster clock speed, the EDVAC performed a calculation in about the same time as the ENIAC because of differences in architecture. For example, both computers took approximately three

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[59] Flamm, *Creating the Computer*, 260-261. The information is contained in "Table A-1. Principal Developments in Computer Technology."
[60] Flamm, *Creating the Computer*, 13.
[61] Patterson and Hennessy, *Computer Organization and Design*, 52-53.
[62] Stern, *From ENIAC to UNIVAC*, 133. The information is contained in a table entitled "A Comparison of Architecture, Performance, and Physical Characteristics of the Eckert-Mauchly Computers."

milliseconds to complete a multiplication.[63] The EDVAC would nonetheless give superior performance in most applications because of its larger memory and more effective design, not to mention easier programming. However, as a general rule, speed and size of memory are the main factors of performance, particularly within a given architecture, and the four technologies noted by Flamm have been essential to increasing either speed or size of memory, or both. They have also been key to reducing costs, energy consumption, and size of computers, and for improving reliability.

John Bardeen, Walter Brattain, and William Shockley of the Bell Telephone Laboratories (BTL) are credited with inventing the transistor in the late 1940s and shared a Nobel Prize in physics for their genius. Transistors substituted for vacuum tubes and thus are used as simple switches and amplifiers. Manufacture of transistors begins with semiconductors, which are elements such as germanium or silicon that are not in themselves good conductors of electricity. Other materials are carefully added to the semiconductor raw material to make the transistor either conduct or halt the flow of electricity upon command. The manufacturing process proved difficult to master, and the first transistors were unsatisfactory: They were unreliable, prohibitively expensive, and slower reacting than vacuum tubes. Government assisted with the development of transistors because, compared to vacuum tubes, transistors are small, use little power, and require no warm up.[64] Flamm reported that government paid about 25 percent of the BTL's research budget in semiconductors for 1949 through 1958.[65] The TRADIC, built by the BTL in 1954 for the Air Force, used only transistors but performed at speeds close of computers with vacuum tubes.[66] The first commercial computing machine with transistors was the IBM 608 Calculating Punch, an updated punched-card calculator.[67] Before it began shipping in late 1957, IBM decided that all their new computers would incorporate sold-state circuitry.[68]

An integrated circuit is a complete electronic circuit, including transistors, often many millions of them, manufactured on a small monolithic piece of semiconductor called a chip. Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor independently invented the

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[63] Flamm, *Creating the Computer*, 9. Information on arithmetic-processing speeds of select early computers is contained in "Table 2-1. Progress in Machine Computation Speeds."
[64] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W. W. Norton, 1997), 202-203.
[65] Flamm, *Creating the Computer*, 15-16. See also "Table 3-1. Early U.S. Support for Computers," 76-77.
[66] Riordan and Hoddeson, *Crystal Fire*, 204. TRADIC is an acronym for TRAnsistorized Digital Computer.
[67] Rosen, "Electronic Computers," 21.
[68] Bashe, et al., *IBM's Early Computers*, 386-387.

integrated circuit in the late 1950s. For their achievement, Kilby, but not Noyce, won a Nobel Prize. Noyce died before the award was made in 2000. Neither man used public funding for their invention but knew the military provided a certain market.[69] As with transistors, government directly or indirectly paid some subsequent development costs. One year after inventing integrated circuits, Texas Instruments used them in a computer for the Air Force.[70] Integrated circuits then became the essential ingredient of the extraordinarily advanced and relatively cheap computers of today. Integrated circuits are commonly used in both processors and memories. Those in memories are specially designed with millions of microscopic capacitors to hold the charges that represent data.

Improving memory has been more difficult than increasing computational speed and has meant making complex compromises between access speeds and costs. Von Neumann recognized that although a computer designer might wish for a "memory organ" of infinitely large capacity, a workable alternative could consist of, "a hierarchy of memories, each of which has greater capacity than the preceding but is less quickly accessible."[71] Computer engineers have indeed found that carefully designed memory hierarchies, based on fundamental principles of compromise and the inverse relationship between speed and size, can create the "illusion of unlimited fast memory." Many refinements to the von Neumann architecture have defined configurations of memory hierarchy and how the levels interact together and with the processor.

At the top of a typical memory hierarchy, designers place a relatively small, expensive, but fast-access memory to work directly with the processor. In fact, it can be said that the highest memory is an integral part of the processor. A computer uses a small number of registers within its processor to hold data immediately before being logically manipulated or moved to the next lower-level memory. All data in an electronic digital computer are contained in discrete voltage signals referred to as strings of zeros and ones. Each zero or one is called a bit.[72] The number of bits in a register is called a word, even when the data represent numbers or other symbols other than letters of the alphabet. Besides being more remote, each consecutive lower level of the memory hierarchy is larger, slower, and less expensive. First is cache memory, perhaps several levels, which operates immediately with the processor, at its speed, and functions as a buffer with the main memory. Main

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[69] Riordan and Hoddeson, *Crystal Fire*, 254-275.

[70] Flamm, *Creating the Computer*, 17-18.

[71] Arthur W. Burks, Herman H. Goldstine, and John von Neumann, *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, 1946; reprinted in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks (Cambridge, Massachusetts: MIT Press, 1987), 101.

[72] Bit is an acronym for Binary digIT.

memory is random access memory (RAM), by which is meant that access time is the same no matter where in memory data is stored. Beneath main memory and at the bottom of the hierarchy is secondary memory. It usually includes magnetic discs or tape.[73]

The memory hierarchy of the ENIAC had at bottom a secondary memory of punched cards, just as used in accounting equipment. Cable connections and switch settings comprised a memory of sorts, and the ENIAC also had three function tables as read-only storage. The function tables were constructed from special resistive-matrix circuits that did not require vacuum tubes. However, Eckert and Mauchly used vacuum tubes to construct a main memory of equivalent capacity to about that in the registers of a computer today. The ENIAC had in fact no higher memory, so its main memory, technically dual-function accumulators, served as registers. A vacuum tube memory was fast acting but necessarily limited in capacity, because vacuum tubes were expensive, bulky, and prone to failure. They also took lots of electricity and generated large amounts of heat. As it was, the ENIAC had an inordinate number of vacuum tubes. Experts in electronics thought the ENIAC had exceeded the practical number of tubes, and though it worked well given its limitations, no one thought it feasible to add more. The main memory of the ENIAC was thus pitifully insufficient and not expandable.[74] Overall, the ENIAC stored up to twenty words of ten decimal digits each in main memory and less than 400 words in function tables.[75]

A computer needs far more high-speed memory, so Eckert developed mercury delay tubes as elements for the main memory of the EDVAC. The mercury delay tube derived from an invention by him during the war for use with radar, but based on an earlier invention by William Shockley of the BTL, the same person who helped invent the transistor. The mercury delay tube converted electrical signals to slower speed pressure waves in mercury and then back to electrical impulses. By amplifying its output and recycling that signal as input back into itself, the mercury delay tube could regenerate and store data indefinitely in sequential mode. The device was thus not random access, but that seemed to pose little problem for the EDVAC with its serial architecture and 1 million pulses

[73] Patterson and Hennessy, *Computer Organization and Design*, 16-20, 97, and 454-455.
[74] That is, not expandable with vacuum tubes. One modification to the ENIAC added a magnetic core memory. See, Randell, *The Origins of Digital Computers*, 299.
[75] More precisely, according to Eckert, the ENIAC contained the storage equivalent of 227 decimal digits in its accumulators and 3,952 decimal digits in its function tables. Counting various program controls, Eckert estimated total internal memory to have been about 7,000 digits. J. Presper Eckert, Jr., "A Preview of a Digital Computing Machine," 15 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 112.

per second clock rate. The EDVAC contained 256 mercury delay tubes, each of which could store thirty-two words of thirty-two bits each.[76] It used a variety of devices for secondary memory and input and output of data. These included Teletype tape, punched cards, and eventually, a magnetic drum.[77]

Von Neumann and his group chose a primary read-write regenerating memory for the IAS computer based on the Williams tube, at heart an ordinary cathode ray tube, after giving up waiting on a similar but more sophisticated memory to be developed by RCA.[78] A cathode ray tube is the main component of a television and may seem odd to use as a memory, but a television picture serves as a kind of temporary memory. The Williams tube swept the phosphor on its five-inch screen many times a second with an electron beam,[79] but instead of a picture left a charged pattern of dots and lines or other two-form combination representing zeros and ones. Wire mesh mounted opposite the screen established a capacitive coupling to help hold the charges. Cathode ray tube memories were also called electrostatic memories for that reason. Memory was periodically read by having the electron beam generate only one form as it swept the screen. If the form matched that stored at the location being read, no change in voltage was detected at the wire mesh. If the form did not match, a voltage change occurred. The signal that resulted at the wire mesh as the beam moved from location to location across the screen was amplified and either routed to the processor or used to regenerate the pattern in memory.[80] The Williams tube originally stored data serially like the mercury delay tube and held the same number of bits. Engineers at Princeton modified the Williams tube to make it random access and give it an access speed sixty times faster than the mercury delay tube. They linked forty of the cathode ray tubes in parallel as a main memory.[81]

The Williams tube did not make a satisfactory memory either, however. Memories made from vacuum, mercury delay, and cathode ray tubes all suffered reliability problems. Magnetic

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[76] Arthur W. Burks, "From ENIAC to the Stored-Program Computer: Two Revolutions in Computers," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 335-339.

[77] S. E. Gluck, "The Electronic Discrete Variable Computer," *Electrical Engineering* 72, no. 2 (February 1953), 162.

[78] F. C. Williams of Manchester, England, invented the Williams tube. RCA went on to perfect the Selectron, or "selective electrostatic storage tube." It was more complex than the Williams tube but used in a number of computers, including the JOHNNIAC. See Jan Rajchman, "Early Research on Computers at RCA," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 468.

[79] Goldstine, *The Computer from Pascal to von Neumann*, 310-311.

[80] J. P. Eckert, "A Survey of Digital Computer Memory Systems," *Proceedings of the I.R.E.* (October 1953), 1397-1399.

[81] Goldstine, *The Computer from Pascal to von Neumann*, 312.

memories perform better, although rotating magnetic storage devices actually work at intermediate speeds. The IAS computer had as its secondary memory an early magnetic drum memory.[82] Engineering Research Associates (ERA) built the first rotating magnetic memories for the Navy and National Security Agency. Ex-Navy scientists had formed ERA after the war to build cryptanalytic equipment for the Navy.

Among magnetic memories and other devices it built, ERA is notable for another early stored-program computer. Unlike the BINAC, the Atlas worked reliably from its delivery to the Navy in late 1950. The Atlas contained 2,700 vacuum tubes and used a rotating magnetic drum as main memory. ERA also produced commercial versions of the Atlas and a more advanced computer, the ERA 1103.

ERA, like Eckert and Mauchly's EMCC, had financial problems, in large part because its major program developing cryptanalytic equipment had little relationship to digital computers and ultimately failed.[83] Even so, ERA was the most successful commercial producer of computers until also bought by Remington Rand in 1952.[84] Acquisition of EMCC and ERA made Remington Rand the largest manufacturer of computers until IBM took the lead in the mid-1950s.

Magnetic or ferrite core memories were a great improvement for high-speed applications, considering storage density, access speed, reliability, and cost. Core memory consisted of arrays of tiny rings of ferrite material with multiple fine wires threaded through their hollow centers. The wires carried current that magnetized the rings in a clockwise or counterclockwise direction corresponding to a zero or one. The wires also read the magnetic states of the rings. Another big advantage to core memory was that it did not need regeneration except when read. Moreover, the cores tended to retain their magnetic states even through a power loss. Historians of computers attribute the invention of core memory to the Whirlwind computer project at the Massachusetts Institute of Technology (MIT), with funding from the Navy and Air Force.[85] Magnetic core memories remained popular into the 1970s, when integrated circuits completely took over as high-speed memory elements of choice.[86]

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[82] Aspray, *John von Neumann and the Origins of Modern Computing*, 80-83.
[83] Colin Burke, "A Practical View of Memex: The Career of the Rapid Selector," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, ed. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 159-160.
[84] Flamm, *Creating the Computer*, 19 and 43-46. See also, "Table A-1. Principal Developments in Computer Technology," 260-261, and "Table A-2. Key Developments in Memory Technology," 262; Erwin Tomash, "The Start of an ERA: Engineering Research Associates, Inc., 1946-1955," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 485-495.
[85] Redmond and Smith, *Project Whirlwind*, 183-190 and 204-207.
[86] Patterson and Hennessy, *Computer Organization and Design*, 525-523.

Flamm noted in summary that from 1945 until 1955 the federal government contributed the great share of money for computer development. Private sources funded no more than 25 percent in 1950, for instance. The public sector also purchased most computers, about 70 percent in 1953. Two years later the situation had changed dramatically: Government operated less than 40 percent of all computers in 1955. Ten years after that, however, public sources still provided about half of all money for computer research in the U.S.[87] The decreasing percentage involvement did not mean less federal money; on the contrary, while other research areas had funding reduced occasionally, government expenditures in computer development grew almost every year. The federal government spent over $1 billion in computer research in 1995, the big share for supercomputers.[88] Rather, the lower involvement as a percentage by government reflected spectacular growth in computer and related industries and huge expenditures by those industries in research. The result has been steady innovation and dramatically lower prices.

Forbes magazine reported in 1997 that the chief business of thirteen of the top one hundred U.S. companies was computers or associated technologies. The list included corporate giants such as Microsoft, Intel, Oracle, Computer Associates, and Compaq Computer, which did not exist in 1955.[89] One company that did, IBM, had most of its sales then from typewriters, time recording devices, and punched-card tabulating equipment.[90] Impact of the computer industry went beyond sales of computers and related items, of course, since much of the equipment was put to work as aids to boost productivity. Technological innovation is a major factor in productivity, which must increase for standard of living to improve.[91] Some evidence suggests that computers may be paying great productivity dividends. According to one account, manufacturers who computerized saw about 5.7 percent per year growth in productivity between 1990 and 1996. Those that did not use computers had 2.6 percent annual growth.[92] Since approximately 85 percent of workers used computing

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87 Kenneth Flamm, *Targeting the Computer: Governmental Support and International Competition* (Washington, D.C.: Brookings Institution, 1987), 25, 42-43, 95, 96-97, 107-108, and 241.
88 National Science Board, *Science and Engineering Indicators—1996*. Washington, D.C.: U.S. Government Printing Office, 1996 (NSB 96-21). "Appendix table 4-22: Federal Obligations for Basic Research, by Science and Engineering Field: FYs 1985-95," and "Appendix table 4-23: Federal Obligations for Applied Research, by Science and Engineering Field: FYs 1985-95," 137 and 139.
89 Editors of *Forbes*, "Steel versus Silicon," *Forbes* 160, no. 1 (7 July 1997), 130. *Forbes* termed these companies "silicon-based companies" because of their dependence on integrated circuits.
90 Emerson W. Pugh, *Building IBM: Shaping an Industry and its Technology* (Cambridge, Massachusetts: MIT Press, 1995), xi.
91 "A Survey of Innovation in Industry," *The Economist* 350, no. 8107 (20 February 1999), 7.
92 Matt Siegel, "Do Computers Slow us Down?" *Fortune* 137, no. 6 (30 March 1998), 34. The information is contained in a table entitled, "Labor Productivity in U.S. Manufacturing: Annual Growth Rates."

technology in some form,[93] it was commonly believed to have been one key to the stellar performance of the U.S. economy through most of the 1990s.[94]

Computers themselves have changed. They fundamentally tend to be von Neumann machines, but smaller and more sophisticated then he could have imagined. Advancements in integrated circuits have led to microprocessors that have extensive computing capabilities on single silicon chips. Use of microprocessors has helped shrink computers from the size of the first large mainframes to that of personal or notebook computers or smaller. Yet computers have become ever more powerful. It is axiomatic that the power of new computers doubles every twelve to eighteen months. This relationship is known as Moore's Law.[95] Tasks given computers have moved so far beyond data processing or mathematical modeling that it is not hyperbole for historian of computers Paul E. Ceruzzi to claim: "A computer is universal machine; it can do 'anything'—that is, whatever we can program it to do."[96] Microelectronics has furthermore promoted merging of computing with instrumentation and communications devices. An estimated 41 percent of American households in 1997 had computers, but they are more common than that figure indicates. Microprocessors are embedded in everyday appliances and services, such as automobiles, wristwatches, thermostats, telephones, and the Internet, integrating computing capabilities in ways not necessarily obvious. The term ubiquitous computing has been coined to describe a pervasive but unseen computer environment that looks to be our future.

Little wonder, therefore, that advocates of state funding of science tout the computer as an example of its fruit. Government spent massively on information-processing technologies during World War II, spent ever increasing amounts thereafter, and the computer is today of tremendous importance. Historians agree that without that support computers simply could not have developed. As one put it, speaking a near-unanimous view: "The failure of large corporations to take the initiative in developing computers during the immediate postwar period meant that if these devices were to be developed at all, the government would have to become the principal financial agent."[97]

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93 James W. Cortada, "Commercial Applications of the Digital Computer in American Corporations, 1945-1995," *IEEE Annals of the History of Computing* 18, no. 2 (1996), 18.
94 "A Survey of Innovation in Industry," *The Economist*, 8.
95 The law is attributed to Gordon Moore, a founder with Robert Noyce of Intel Corporation, a major manufacturer of microchips.
96 Ceruzzi, *The Reckoners*, 151.
97 Stern, *From ENIAC to UNIVAC*, 160.

Nor is the computer the only major technology alleged to have resulted from federal monies dispensed for research during the war. Jet engines, rockets, DDT, and penicillin were others.[98]

Inspired by successes epitomized by the computer, it became a fact of life for federal government to spend enormous amounts of money for research. Many innovations have been created and commercialized. The United States has prospered. Nonetheless, contrary to prevailing wisdom, history suggests that the same computers would exist today without that government involvement but with less money having been spent. Economic efficiencies were of secondary importance at best, of course, since support initially came during national crises. The computer is in that sense a weapon converted to plowshare. The issue is not to question the need for defense, but to consider whether spending on computer development by government was otherwise warranted.

Evidence that public support was unnecessary is of various kinds. First, there is the history of invention generally. People were prolific innovators before lavish support by government became commonplace. There is no reason to think inventing would have stopped if not for the new assistance, although the invention rate did decline. That is, counterintuitive though it may seem, patents awarded *per capita* decreased approximately coincident with the rise of government support. Second, examination of innovations related to computers and developed with government support suggests the private sector was quite willing and able to perfect them on its own. Third, review of the experiences of other nations gives evidence that government intervention in computer development was not only unnecessary but also counterproductive. Fourth, a data-handling industry existed before World War II. It was cautious but nevertheless innovative and highly responsive to customers, who were notoriously price sensitive.[99] The history of the industry, particularly of IBM, suggests it would have built computers to meet growing information-processing needs of corporations and governments. Finally, the history of modern computers begins not with the ENIAC, but earlier. The foundation of electronic digital computers lies in the seemingly unlikely depths of the Great Depression, which were actually highly productive years for innovation generally. So important were the achievements of the prewar years that it could be said that the commercial success of the computer was due not to government, but rather, the successes of government-developed computer

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[98] *Science Policy Study Background Report No. 1: A History of Science Policy in the United States, 1940-1985* (Washington, D.C.; U.S. Government Printing Office, 1986), 20.

[99] James W. Cortada, *Before the Computer: IBM, NCR, Burroughs, and Remington Rand and the Industry they Created, 1865-1956* (Princeton, New Jersey: Princeton University Press, 1993), 4-5 and 105-110.

technology depended on privately funded work. The computer in that sense can better be described as a plowshare converted to sword.

Notable in prewar work was that of John Vincent Atanasoff and Clifford Berry, a young professor of mathematics and physics and one of his graduate students, respectively, at Iowa State College (now University) in Ames, Iowa. A federal district judge ruled in 1973 that they, not Eckert and Mauchly, invented the first automatic electronic digital computer. Although Eckert and Mauchly could not patent the EDVAC, they did eventually patent the ENIAC. They then sold a large share of the rights to that and other of their patents to Remington Rand, which in 1955 merged with Sperry Corporation to become Sperry Rand. Honeywell, Inc., challenged the patents and uncovered evidence of the primacy of the computer by Atanasoff and Berry. At the time of its invention in the late 1930s and early 1940s, that computer did not have an official name, or at least none with lasting historical resonance. It has since come to be called the Atanasoff Berry Computer, or ABC.[100] Earl E. Larson, presiding judge over *Honeywell v. Sperry Rand*, found not only the ABC to have been first computer, but also that Eckert and Mauchly used ideas from it key to the ENIAC without giving credit. As it happened, Mauchly had visited Atanasoff in Iowa, stayed as a guest in his home, and conducted a thorough study of the ABC as it neared completion nearly two years before he and Eckert began the ENIAC.

Historians of computers have been skeptical of Judge Larson's decisions. They accept that Mauchly got ideas from Atanasoff and Berry but have not believed them crucial to the ENIAC, which they think the more influential machine. In defense of that position, Mauchly vehemently denied learning or using anything important from the ABC. Adding substance to his denial is that the earlier computer had little in common with the ENIAC. Almost its opposite, in fact, the ABC was about the size of a desk and weighed approximately 750 pounds. It cost about $3,600, although a less probable reading of records gives a cost of $5,460, at least of those expenses recorded.[101] Moreover, while the

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[100] R. K. Richards coined the name Atanasoff-Berry computer (with a hyphen and a small c) in *Electronic Digital Systems* (New York: John Wiley and Sons, 1966). In some legal documents, the computer is referred to as the Atanasoff-Berry Computer (with a hyphen and a capital c). John V. Atanasoff subsequently decided the name should be Atanasoff Berry Computer (with no hyphen and a capital c). That name is used here per his wish. John V. Atanasoff and Alice Atanasoff, letter to Clark Mollenhoff, 7 December 1986. ISU, Parks, "Clark Mollenhoff Papers, 1968-1990" (box 1, folder 20).

[101] As of August 1940, $1,460 had been spent on construction of the ABC. See John V. Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," August 1940; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 334. Atanasoff then received a grant of $5,330 from the Research

ENIAC performed a variety of computational tasks, the ABC did only one thing directly: solve sets of linear algebraic equations, which it did at an operational rate of sixty pulses per second as timed by an electric motor. Finally, Atanasoff and Berry never finished or patented the ABC. That was because they saw little potential in it, according to a commonly held opinion. If Mauchly said he learned nothing from the ABC, it has seemed safe to conclude that the ABC had no further impact. Rather than first electronic digital computer, the ABC was more historical curiosity.

It is a pity historians have not seriously studied the ABC, because the truth is quite different. The ABC did not resemble the ENIAC, because it had more in common with modern computers. Unlike computers today, the ENIAC did computations by counting with decimal numbers in accumulators, which served dual purpose as main memory. Besides being highly parallel, the ENIAC had features including function tables, a multiplier, and other components that added clutter. Design of the ENIAC emphasized operational speed, narrowly defined, above all else, and Mauchly believed big equipment necessary to attain it.[102] By contrast, Atanasoff and Berry understood instinctively the value of compromise and that bigger is not necessarily better. They gave the ABC a simple, efficient, and effective design. Like computers today, the ABC did not use function tables or a multiplier. Rather, presaging von Neumann machines, its mixed architecture included, besides input and output devices, distinct arithmetic processing, controls, and memory units.

The memory in particular caught people's attention. Atanasoff had wanted a magnetic memory.[103] Because he anticipated a small budget, however, he settled on a more economical one consisting of banks of capacitors mounted in wax inside two identical drums turned by the same motor that provided timing. Despite its much smaller size, the ABC had over four and one-half times

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Corporation. Best estimate is that $2,134 of that was spent. The estimate comes from a hand-written accounting slip labeled "Research Corporation Grant to Anatasoff (sic)," 25 May 1948, and which indicated a balance of $3,196.10 in the account. It is possible the figure actually indicated the amount spent. If so, it is closer to Atanasoff's recollection as noted in unsigned memo entitled "Electronic Computers" and dated 26 June 1948. According to the author (an ISC official assumed to be R. E. Buchanan; see, John Vincent Atanasoff, New Market, Maryland, transcript of interview with B. Kaplan, 23 August 1972, 130-132, Smithsonian), Atanasoff reported about three-quarters of the money from the Research Corporation grant had been spent. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).

[102] John W. Mauchly, "Digital and Analogy Computing Machines" 8 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 32.

[103] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 318; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Transcript of Proceedings," 2,658. ISU, Parks, "John Vincent Atanasoff Papers" (box 44, folder 1).

the read-write memory of the ENIAC.[104] To ensure integrity of data, the ABC had a mechanism for automatically refreshing, or regenerating, charges in the capacitors. Integrated circuit memories of today likewise use capacitors as storage elements that are continually refreshed. And like computers today, decimal numbers were entered into the ABC and automatically converted to their binary equivalents. The ABC then did computations electronically in binary using switching logic. Atanasoff and Berry's computer was a most ingenious and elegant machine, one whose characteristics are fundamental to computers still.

While the ABC solved only linear simultaneous equations, those equations have many applications. A major purpose for the IAS computer was to deal with sets of linear algebraic equations, which are impossibly laborious to solve with pencil and paper in sets larger than ten equations and ten unknowns.[105] Design of the ABC allowed solution of equations sets up to twenty-nine unknowns. The tiny memory of the ENIAC made it an extremely cumbersome tool to attempt such large equation sets.[106] Furthermore, the smaller word size of the ENIAC meant much less accurate answers. The ABC had a binary word size equivalent to fifteen or sixteen decimal places, compared to ENIAC's normal ten.

Nor would the ENIAC necessarily have solved problems faster than the ABC. As discussed, the best measure of computer performance is not pulses per second but application completion time. The ENIAC did calculations electronically in its accumulators, but with so little read-write memory it had to transfer partial results through input and output devices at slow electromechanical speeds. The transfers significantly compromised performance. The ENIAC could on average complete seventy multiplications in the time it took to produce one output,[107] a mismatching described as "absurd" even by one research associate on the ENIAC project.[108] The ABC could also have performed calculations at electronic speeds, but Atanasoff and Berry chose instead a balanced design that orchestrated all components precisely in harmony.[109]

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[104] The ABC had sixty words, or 3,000 binary digits, of read-write memory. That was equivalent to about four and one-half times the capacity of the ENIAC, which had twenty words, or 200 decimal digits, of read-write memory.
[105] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 316.
[106] Burks and Burks, *The First Electronic Computer*, 268.
[107] Aspray, *John von Neumann and the Origins of Modern Computing*, 62.
[108] Chuan Chu, "Magnetic Recording," 31 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 310-311.
[109] Atanasoff estimated the electronic circuits in the ABC could complete an operation in about twenty-five microseconds. *Honeywell*, "Transcript of Proceedings," 2,080-2,081; 2,629-2,655; and

It is estimated therefore that the ENIAC could have been no more than seven times faster than the ABC from initial input to final results in solution of simultaneous equations.[110] That estimate is based on relative speeds of data handling and calculations, however. Organization of the solution method posed an additional problem for the ENIAC. Two complete equations with twenty-nine unknowns each could be loaded into the ABC and dealt with simultaneously, but the ENIAC could have handled about a third as many unknowns at best. Thus, in equations sets that mattered—the large ones—the ENIAC might not have been as fast as the ABC. The difference in true computational rates of the two computers was nothing like that suggested by their difference in operations per second.

The ABC might also have been faster than the ENIAC in solution of many differential equations. Atanasoff and his students developed a method for approximating linear differential equations using linear algebraic ones. In fact, the main purpose of the ABC was to deal with complex differential equations whose solutions could not be solved analytically, but only approximated. Atanasoff therefore observed that the initial application of the ENIAC, the hydrogen bomb problem, which took some weeks over several months to solve, likewise by an approximating method, might have been completed faster and more accurately on the ABC.[111] The problem involved three simultaneous partial differential equations. If the equations were linear, the ABC was better suited for their solution. The ABC had impressive powers, even if it could not have handled the assortment of tasks of the ENIAC. Reprogramming the ABC meant rewiring its controls. That was also true of the ENIAC, but rewiring it was easier.

In short, the relative advantages of the ABC and ENIAC depended on application. For all practical purposes, the ABC was the better machine for linear algebraic equations. In solution of other problems, especially differential equations, another major task for early computers, the ENIAC

2,671; John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 24 May 1972, 123-124. Smithsonian.

[110] Charles G. Call, of Bair, Freeman and Molinare, memorandum to Henry Halladay, of Dorsey, Marquart, Windhorst, West and Halladay, 1 October 1968. The details are explained in an attachment entitled, "Comparing the Operating Speeds of ENIAC with the Atanasoff-Berry Computer," 1-8. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 7).

[111] Call, attachment to memorandum to Halladay, 1 October 1968, 8-9. The "Los Alamos problem" involved the use of "three simultaneous partial differential integral equations" to investigate mixtures of deuterium and tritium needed to create a hydrogen bomb. See also comments by Kay McNulty (later Kay Mauchly), who helped program the ENIAC for the hydrogen bomb problem: McNulty quoted in Fritz, "ENIAC—A Problem Solver," 32-33. Further discussion is contained in John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 25 July 1968, 29-56. ISU, Parks, "John Vincent Atanasoff Papers" (box 33, folder 2).

served better in simple and repetitive applications needing low accuracy, such as ballistics tables. For scientific problems involving more complex equations and demanding higher accuracy, the ABC was better suited when the equations could be transformed into linear algebraic equations. The distinction of the ABC being special purpose, or slower, is not particularly meaningful given the limitations of both machines and the state of applied mathematics. More to the point, in effectiveness of technology, the ABC greatly bested the ENIAC costing over one hundred times more.

It is true that Atanasoff and Berry did not apply for a patent on the ABC, but the reason was not because they thought it lacked value. They knew it held great promise. In fact, rather perversely considering patents are intended to facilitate availability of inventions, Atanasoff stifled notice of the ABC to avoid the type of situation that prevented patenting the EDVAC. That is, Atanasoff understood that premature disclosure could disqualify the ABC for patenting, and he and Berry very much wanted to patent it.

As it happened, the U.S. entered World War II before the ABC could be completely debugged and placed into regular operation. Both Atanasoff and Berry left Iowa State College (ISC) by mid-1942 because of the war. They believed that the ABC worked mostly satisfactorily, although it did have a problem with a custom-designed input-output mechanism. Like the ENIAC, the ABC depended upon paper cards as secondary memory. Instead of punching holes, the ABC charred spots with high voltage arcs. An input device similarly used electric arcs to detect differences in resistance associated with the charred spots. Occasionally the read-write mechanisms failed. The two men thought the trouble was in the paper, and as they prepared to depart from ISC, they asked a student helper to procure a type that they believed might work without error. The student failed, and neither Atanasoff nor Berry returned permanently to ISC. The ABC got set aside amidst the turmoil and exigencies of the war and eventually scavenged for parts and scrapped without approval from Atanasoff.

Furthermore, Atanasoff made arrangements for a patent attorney to prepare an application. It did not get filed for a number of reasons. These included lack of qualified personnel remaining at ISC during the war who could assist, questions of how to deal with a radical invention, Atanasoff's total commitment to urgent and difficult wartime projects, his separation from family, and marital problems that led to a divorce. The war years were highly stressful for Atanasoff. He seemed to have assumed the war would be brief and he could return quickly to ISC. With so much going on, the ABC simply got away from him. The sad truth is that the ABC became a casualty of the war, just as the ENIAC was its progeny.

The ABC was not a true computer, being neither general purpose nor stored program. Nor was it any more automatic than the ENIAC. Operating the ABC required constant manipulation of data cards and controls. Judge Larson had a false choice to make in having to decide whether the ABC or ENIAC was the first modern computer in the sense the term now means. Atanasoff designed and built the ABC with substantial help from Berry. The two men knew such computers could do a wide range of tasks and even be made general purpose. However, Atanasoff candidly admitted that they had not by themselves made the intellectual leap to the essential stored-program concept,[112] even as they defined its prerequisite technology, a large and effective memory. Related, a true computer must make conditional decisions, and the ABC could not do that in a meaningful sense. Atanasoff understood conditional branching, but his computer did not need that capability.[113] He and Berry cannot therefore be credited with conception of the computer in total. Resemblance of the ABC to the modern computer is probably not coincidence, however. Atanasoff and Berry, directly and indirectly, influenced subsequent computers through Eckert, Mauchly, and others.

Even if not obvious and though Mauchly refused to admit it, essential features of the ENIAC did come from the ABC, as Judge Larson correctly found. More important, when weaknesses in the ENIAC design finally became apparent to Eckert and Mauchly, they returned to concepts pioneered in the ABC. They used some of Atanasoff and Berry's ideas in the ENIAC; they used more in the EDVAC. It is unfortunate for that reason that the EDVAC did not get patented. The lawsuit that would have inevitably followed might have helped sort through the origins of the EDVAC as the Honeywell trial did for the ENIAC. Eckert and Mauchly did patent the mercury delay tube memory of the EDVAC, and Judge Larson ruled that patent unenforceable because of its derivation from the ABC. Except for its stored-program capability and serial architecture, which von Neumann championed, the EDVAC's basic characteristics were also those of the ABC. In its internal number base, division into distinct units, regenerating memory, use of switching logic in computations, and overall elegant design, the EDVAC reflected the ABC.

Eckert briefly considered building a computer with a magnetic memory to improve on the ENIAC. In an early-1944 memorandum, he proposed a "numerical calculating machine . . . driven by

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[112] John Vincent Atanasoff, "Advent of Electronic Digital Computing," *Annals of the History of Computing* 6, no. 3 (July 1984), 230; Atanasoff, interview with Kaplan, 23 August 1972, 64-67.
[113] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 10 July 1968, 51-61. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 4).

an electric motor" that incorporated magnetic discs for read-write storage. Eckert said he got the idea from Perry Crawford, a graduate student at MIT who in 1942 wrote an influential thesis that sketched out fundamentals for an electronic digital system for control of antiaircraft guns.[114] The thesis discussed binary numbers, electronic switching circuits, motor-driven timing, and magnetic storage of data on discs, among other things.[115] The proposal by Eckert also sounds like a version of the ABC with magnetic memory, the computer Atanasoff wanted to build had he the resources and of which Mauchly knew. For example, Eckert's proposed computer stored numbers serially on magnetic discs the same way the ABC stored numbers serially in its memory.[116]

Eckert, like Mauchly, claimed to have learned nothing from Atanasoff and the ABC. However, in a journal article published in 1953, Eckert credited Atanasoff for developing the "first example of what might generally be termed regenerative memory," meaning the capacitor memory of the ABC.[117] The admission came back to haunt Eckert when presented as a portion of the evidence that the mercury delay tube memory derived in part from the regenerating memory of the ABC.[118]

Furthermore, contact of Eckert and Mauchly with Atanasoff did not end with Mauchly's visit to ISC. Both Eckert and Mauchly went to him for additional guidance. Eckert shelved the idea of a magnetic disc memory in favor of the mercury delay tube, whose faster-acting vital elements were quartz transducers that converted electrical energy to sound waves in mercury and vice versa. Unable to get the delay tubes to function properly, he and Mauchly sought assistance in August 1944 from Atanasoff, then doing research in acoustic mines at the Naval Ordnance Laboratory (NOL) near Washington, D.C. Atanasoff had studied the physics of quartz crystals at ISC, and combined with his acoustics, electronics, and computer experience, there was no one more qualified with whom they could consult. Atanasoff recalled the two men saying they had "difficulty getting a signal of

[114] J. Presper Eckert, "Disclosure of Magnetic Calculating Machine," 1944; reprinted in "The ENIAC," 530-531 and 537-539.
[115] Perry Orson Crawford, "Automatic Control by Arithmetical Operations," unpublished M.S. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1942.
[116] Eckert's 1944 memorandum is otherwise significant because it gives evidence that he thought of the rudimentary stored-program concept before meeting von Neumann, having instead gotten the idea from organs of the music-making kind. Eckert proposed discs be "engraved," so as to permanently store, "such pulses or other electrical signals as were required to time, control and initiate the operations required in the calculations. This is similar to the tone generating mechanism used in some electric organs." See, Eckert, "Disclosure of Magnetic Calculating Machine," 537.
[117] Eckert, "A Survey of Digital Computer Memory Systems," 1,394.
[118] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Action No. 15,823 and No. 15,824, "Deposition of Dr. John William Mauchly," 161-168. ISU, Parks, "John Vincent Atanasoff Papers" (box 19, folder 6).

sufficient strength."[119] He obligingly explained that the problem likely resulted from interference among the pressure waves as they flowed down the tubes, and he suggested that the best solution meant redesigning the transducers to introduce "plane wave(s) without distortion" into the delay lines.[120] When Eckert persisted, Atanasoff agreed to take time from his already brutal schedule of top-secret military research to help further if arrangements could be made through channels. A request was initiated through the Army by Eckert's supervisor, John G. Brainerd, but no contract materialized at the NOL.[121]

Mauchly had more contact with Atanasoff, including discussions on computers.[122] He began visits at the NOL early in 1943 that continued, often once or twice a week, until after the war. Besides helping with the ENIAC, Mauchly also worked as an instructor at the University of Pennsylvania. He then lost his teaching position, because he said, he suffered from anemia. Despite his health problem, he wanted to work full time on the ENIAC, but administrators agreed to increase his salary only modestly beyond his half-time pay. Mauchly took that to imply that he "wasn't worth very much to the project." With his former total salary of $5,800 reduced to $3,900, he obtained through Atanasoff a part-time position at the NOL beginning September 1944. Mauchly at first did statistical analysis for the Navy under contract to Iowa State College, in effect becoming an employee of ISC. He later became a civil service employee.[123] Mauchly had opportunities during those months to learn more from Atanasoff useful in the EDVAC.[124]

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[119] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 23 July 1968, 38. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 7).

[120] *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Dr. John V. Atanasoff," 865-868. ISU, Parks, "John Vincent Atanasoff Papers" (box 30).

[121] *Honeywell*, "Transcript of Proceedings," 2,231-2,234; 2,769-2,771; 2,774-2,778; and 2,890-2,894. See, in particular, J. G. Brainerd, transcript of letter to Captain H. H. Goldstine, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 31 August 1944, 2,891-2,893; and transcript of letter excerpt from Leslie E. Simon, Colonel, Ord. Dept. Director, Ballistic Research Laboratory Division, 2 September 1944, 2,894. ISU, Parks "John Vincent Atanasoff Papers" (box 43, folder 5, and box 44, folder 2).

[122] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 864.

[123] *Honeywell*, "Transcript of Proceedings," 2,228-2,230; 2,753-2,764; 2,775; and 11,912-11,926. See especially, John W. Mauchly, memorandum entitled "Situation as of September 10, 1944," quoted 11,918-11,919.

[124] Actually, how Mauchly came to be employed at the NOL and what he did there has never been satisfactorily explained. Mauchly claimed Atanasoff asked him for assistance. Atanasoff could recall little of the situation but thought Mauchly had sought help from him. Atanasoff, "Advent of Electronic Digital Computing," 265; *Sperry Rand*, "Deposition of Dr. John William Mauchly," 183; Atanasoff, interview with Halladay, et al., 23 July 1968, 22-43; *Honeywell*, "Deposition of Dr. John

The ABC had striking similarities with the EDVAC. It had more in common with the IAS computer. This again was probably not entirely coincidence. Von Neumann obtained practical ideas from Eckert and Mauchly, who had appropriated freely from Atanasoff and Berry. Von Neumann also exchanged ideas directly with Atanasoff. For a few months before he began design of the IAS computer, and for about a year thereafter, von Neumann consulted with Atanasoff, who had responsibility for developing a computer for the NOL. Atanasoff estimated their discussions numbered perhaps no more than five but covered basic computer theory.[125] One meeting between the two men took place over three or four days.[126]

The NOL had decided in April 1945 to establish a centralized computing facility.[127] It asked a couple of scientists before Atanasoff to take charge of the design and construction of a computer,[128] but no one wanted the extra work.[129] Atanasoff, in tight time constraints himself, volunteered reluctantly and gave wide latitude to scientists assigned to it. Even so, under his leadership the NOL computer started to shape into what the ABC might have been given a $300,000 budget and several years' progress in technology. The NOL computer team decided as a start to use internal binary numbers and switching logic. As advancements, the members intended the electronic computer to be general purpose and stored program. It also was to have floating-point number arithmetic (also called scientific notation), convenient for handling very large or small numbers. In floating point, a number is transformed into two components: one for digits and the other to indicate magnitude, that is, the position of the decimal point in relation to the digits. Timing would have come from an electronic or electronic-quartz clock to make it extremely fast.

V. Atanasoff," 1,098: George L. Hamlin, "NSWC's Long List of Connections to the Computer," *On the Surface* 7, no. 36 (21 June 1988), 8.

[125] John Vincent Atanasoff, New Market, Maryland, interview with B. Kaplan, 16 August 1972, 22-27. Smithsonian.

[126] Hamlin, "NSWC's Long List of Connections to the Computer," 8.

[127] Aspray, *John von Neumann and the Origins of Modern Computing*, 235-236.

[128] The NOL computer project was officially termed the 15AK project. John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 24 July 1968, 7. ISU, Parks, "John Vincent Atanasoff Papers" (box 33, folder 1); *Honeywell*, "Transcript of Proceedings," 2,778-2,830.

[129] Calvin and Charlotte Mooers, interview by Kevin D. Corbitt, OH 254, Charles Babbage Institute, University of Minnesota, Minneapolis, Minnesota; Calvin N. Mooers, "Atanasoff at the Naval Ordnance Laboratory," *Annals of the History of Computing* 15, no. 2 (1993), 54-55; Calvin N. Mooers, "Discussion of Ideas for the Naval Ordnance Laboratory Computing Machine," 26 August 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 517-525.

At first, Atanasoff considered a capacitor memory like on the ABC but with electronic switching. The team finally decided on cathode ray tubes to comprise a main memory of about 8,000 words, each fifty binary digits. Secondary memory was to use magnetic wire.[130] The NOL unfortunately aborted the ambitious project in late 1946 for lack of personnel to see it to completion.[131] Little progress had been made on the details of the computer, although more got accomplished on its cathode ray tube memory, the most critical component.[132]

As an aside, Mauchly also worked on the NOL computer project. He claimed he had been involved in general discussions, but Atanasoff had no memory of that. Mauchly did help write job descriptions for the project, however.[133] Perhaps not coincidentally, he stopped visiting the NOL after it canceled the computer.[134] Moreover, despite whatever involvement Mauchly had, the NOL computer project team never considered duplicating the ENIAC, recognized to have an inferior design.[135]

As for Atanasoff, he had little time to devote to the NOL computer. His main duties lay elsewhere. As head of the Acoustics Division for the NOL, he had to give priority to Project Crossroads, tests of two atomic bombs at the Bikini Atoll in summer 1946. The nuclear devices were

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[130] Atanasoff, interview with Halladay, et al., 24 July 1968, 22; Atanasoff, interview with Kaplan, 16 August 1972, 26-27; Atanasoff, interview with B. Kaplan, 23 August 1972, 60-62, 64-65, and 109; Atanasoff, "Advent of Electronic Digital Computing," 257-259; Mooers, "Discussion of Ideas for the Naval Ordnance Laboratory Computing Machine," 517.

[131] Atanasoff, interview with Kaplan, 16 August 1972, 30-31; J. H. Curtiss, "A Review of Government Requirements and Activities in the Field of Automatic Digital Computing Machinery," 1 August 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 360. Calvin Mooers worked on the NOL computer but left the project before the Navy killed it. He claimed von Neumann subsequently told him he had the project terminated because he (Mooers) had left, and that without him, there was no one to work on the project. Calvin and Charlotte Mooers, interview Charles Babbage Institute.

[132] David Beecher, Rockville, Maryland, telephone interview with Paul Mobley, 4, 9, and 10 December 1997; Atanasoff, interview with B. Kaplan, 23 August 1972, 67-71; E. R. Kolsrud, technical report entitled "Storage of Pulses on Cathode-Ray Tubes (AM 178)" to NOL storage, 18 June 1947. ISU, Parks, "John Vincent Atanasoff Papers" (box 10, folder 10).

[133] Mauchly claimed the job description for the director of the project was "written as to fit my background and characteristics because he (Atanasoff) hoped that I would direct and design the computer." Atanasoff said nothing on the issue, but it was unlikely he wanted Mauchly to head the project. Mauchly's supervisor at the NOL had a low opinion of his abilities and said so to Atanasoff. *Sperry Rand*, "Deposition of Dr. John William Mauchly," 180-181; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 1,097; *Honeywell*, "Transcript of Proceedings," 2,754-2,764 and 11,924-11,925; Atanasoff, interview with Halladay, et al., 23 July 1968, 35; Atanasoff, interview with Kaplan, 16 August 1972, 9-11.

[134] Atanasoff, "Advent of Electronic Digital Computing," 259.

[135] *Honeywell*, "Transcript of Proceedings," 2,830.

the first to be detonated postwar and thus first to allow a full complement of measurements. The Navy had special interest in the effects of the explosions on some eighty-five surplus or captured war vessels of all kinds anchored in the target area. One blast was atmospheric and the other, several weeks later, underwater, and Atanasoff had responsibility for making acoustical measurements in air and water. His group also conducted a detailed seismic survey of the atoll. Atanasoff and his technicians spent months preparing, made measurements during eight weeks on location in the South Pacific, then needed more months to analyze data and write reports. As it happened, the NOL computer project was active concurrent with Project Crossroads.[136] Giving Atanasoff no rest, among other special projects, the NOL then assigned him to head another priority project developing a guided missile fired from large naval guns.[137]

The IAS computer evolved into much the same machine that Atanasoff and his NOL team had envisioned, although the IAS computer had less memory and fixed rather than floating-point number representation. Von Neumann decided the more complex circuitry and larger memory required for floating-point representation outweighed its advantages.[138] Computer designers thereafter became cautious about adopting floating-point. Nonetheless, by the late 1950s the majority of computers had the feature.[139]

Despite the similarities between the NOL and IAS computers, it is unknown how much influence Atanasoff and von Neumann had on each other. Atanasoff, never known for false modesty, stated that he had learned from von Neumann.[140] On the other hand, he found the famous mathematician interested in theory of computers but less so in practical design aspects.[141] Another participant remembered the relationship of the two men as that of relative equals, so undoubtedly von Neumann learned a thing or two from Atanasoff.[142] Indeed, at the formal termination of the NOL

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[136] Milton B. Dobrin, Beauregard Perkins, Jr., and Benj. L. Snavely, "Subsurface Constitution of Bikini Atoll as Indicated by Seismic-Refraction Survey," *Bulletin of the Geological Society of America* 60 (May 1949), 807-828; *Honeywell*, "Transcript of Proceedings," 2,243 and 2,279-2,281; Atanasoff, interview with Kaplan, 16 August 1972, 27-32; John Vincent Atanasoff, interview with B. Kaplan, Smithsonian Institution, 17 July 1972, 35-36. Smithsonian.

[137] The guided missile project was called GLGM (Gun Launched Guided Missile). The name later changed to ZEUS. The Navy eventually dropped the project in favor of conventional guided missiles. Among other things, Atanasoff designed an onboard analog guidance computer to direct the missile to its target. Atanasoff, interview with Kaplan, 23 August 1972, 121-128.

[138] Burks, Goldstine, and von Neumann, *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, 407.

[139] Patterson and Hennessy, *Computer Organization and Design*, 250.

[140] Atanasoff, "Advent of Electronic Digital Computing," 258.

[141] Atanasoff, interview with Kaplan, 23 August 1972, 66.

[142] Beecher, interview with Mobley, 4, 9, and 10 December 1997.

computer project, von Neumann praised Atanasoff's knowledge.[143] Atanasoff and Berry had been for a time the foremost experts in electronic digital computers. Three years passed before work began on the NOL computer, but the interim thinking by others did little to shape the IAS computer.[144] *First Draft*, written by von Neumann before he met Atanasoff, overviewed the best ideas, and Atanasoff was an early recipient. The basic concepts it advocated coincided with many of his and Berry's ideas from the ABC, although von Neumann expressed them within a larger context.

Von Neumann explained the stored-program principle to Atanasoff, who believed that the concept had originated with him. However, when Atanasoff asked for suggestions to improve the logic system he and Berry had developed for the ABC, von Neumann could think of none. He instead recommended that the NOL computer use circuits of the same type.[145] Moreover, *First Draft* advocated serial architecture, but von Neumann adopted a mixed architecture for the IAS computer. Since the ABC also had a mixed architecture, this similarity possibly was connected to his association with Atanasoff. The two computers did not have the same architectures, however. The ABC transmitted numbers serially and calculated in parallel. The IAS computer transmitted numbers in parallel and calculated serially. The architecture of the ABC fit its purpose of solving linear algebraic equations, one application for which parallel computing is well suited. The architecture of the IAS computer worked better for general-purpose applications. Another connection between the NOL and IAS computers is that both Atanasoff and von Neumann promoted use of cathode ray tube memories. The concept was generally known, though no one had yet perfected such a memory. It is intriguing that von Neumann described the cathode ray tube memory as "nothing more than a myriad of capacitors," an obvious observation but reminiscent of the design of the ABC.[146]

Aside from Mauchly, Eckert, and von Neumann, there were other likely conduits for dissemination of ideas of Atanasoff and Berry. Historians have assumed that Atanasoff and Berry labored in isolation without recognition beyond ISC. Atanasoff actually encouraged that view. A number of authorities in computers learned of the ABC, however, including the most prominent in the United States. These included Samuel Caldwell of MIT, Thornton Fry of the BTL, and others. Representatives of IBM and similar manufacturers also knew of it. Experts were usually interested

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[143] Atanasoff, "Advent of Electronic Digital Computing," 259.
[144] Atanasoff, interview with Kaplan, 17 July 1972, 19.
[145] *Honeywell*, "Transcript of Proceedings," 2,618-2,619 and 2,744-2,750; Atanasoff, interview with Kaplan, 23 August 1972, 64-67.
[146] Burks, Goldstine, and von Neumann, *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, 102.

and often enthusiastic. For instance. Caldwell gave the ABC a solid endorsement. He went to ISC in 1941 to meet Atanasoff and came away so impressed that he made a recommendation to the Research Corporation. a private organization dedicated to funding research. that it provide money to finish the ABC.[147] Caldwell later became advisor to Perry Crawford on his important thesis on digital controls. Fry. Mathematical Research Director for the BTL. said of the ABC that it was. "entirely realistic. and there is no doubt at all that the machine. when built. will find a wide range of usefulness."[148]

Raytheon Manufacturing Company told Atanasoff that when. "this machine (the ABC) is ready for any commercial applications. we would like very much to have an opportunity to discuss it with you."[149] GE took "considerable interest" in the ABC and asked about "acquiring the right to make and use the machine or in cooperating with the college in its further development."[150] Remington Rand also wanted to negotiate a contract with Atanasoff on the ABC.[151] IBM and Atanasoff had frequent correspondence from early 1937 through construction of the ABC. IBM even supplied several hundred electrical contact brushes for the ABC for free.[152] The company had interest in Atanasoff and Berry's work and allegedly wanted patent rights.[153] It had started its own exploratory efforts in electronic circuits and calculators about the same time as Atanasoff.[154]

Support for the ABC stands in stark contrast to the negative opinions experts had later for the ENIAC. They typically warned the ENIAC was a bad investment. Harold Hazen. Chief of Division 7 of the National Defense Research Committee (NDRC). was one critic. The NDRC had

[147] S. H. Caldwell. Electrical Engineering Department. MIT. copy of letter to Howard A. Poillon. President. Research Corporation. 23 January 1941. ISU. Parks. "John Vincent Atanasoff Papers" (box 47. folder 7).
[148] Thornton C. Fry. Mathematical Research Director. Bell Telephone Laboratories. copy of letter to Howard A. Poillon. President. Research Corporation. 27 March 1941. ISU. Parks. "John Vincent Atanasoff Papers" (box 47. folder 7).
[149] Elmer J. Gorn. Raytheon Manufacturing Company. letter to J. B. Attanasoff (sic). 2 July 1940. ISU. Parks. "John Vincent Atanasoff Papers" (box 26. folder 3).
[150] H. B. Marvin. General Electric Laboratory. letter to John V. Atanasoff. 11 March 1941. ISU. Parks. "John Vincent Atanasoff Papers" (box 25. folder 12).
[151] T. F. Allen. Vice President. Remington Rand. letter to John V. Atanasoff. 11 September 1940. ISU. Parks. "John Vincent Atanasoff Papers" (box 26. folder 3).
[152] For information on one order of brushes. see G. H. Armstrong. Manager of Engineering. IBM. letter to J. V. Atanasoff. 5 February 1940. ISU. Parks "John Vincent Atanasoff Papers" (box 26. folder 2).
[153] Quincy C. Ayres (attributed). Secretary-Manager. Iowa State College Research Foundation. report entitled "Computing Machine: John V. Atanasoff." circa March 1941. 2; See also. for examples: Clement Ehret. Director Market Research. IBM. letters to John V. Atanasoff. 8 February 1940. 16 January 1942. 13 August 1942. and 21 December 1942. ISU. Parks. "John Vincent Atanasoff Papers" (box 47. folder 3 and box 26. folder 2).
[154] Pugh. *Building IBM*. 81-86.

responsibility for directing most wartime research work. Division 7 involved fire control for antiaircraft guns and included some digital control technologies. After reviewing the ENIAC proposal for the Army, he observed that the "techniques proposed were sadly outdated." Furthermore, he did not have, "any reasonable hope that such a device could be brought into use early enough in any case."[155] Caldwell also worked for the NDRC. He indicated mild interest in the ENIAC and thought it similar to a computer considered at MIT and deemed impractical.[156] The Army funded the ENIAC despite advice from outside experts, and even though its own chief scientist in ballistics, Thomas Johnson, recognized the ENIAC proposal as being "a long way behind present art."[157] Flush with public money, the Army backed almost any project with even a remote chance to help with the war.[158]

That the ABC failed to be cited by people who made subsequent advancements does not mean it had no impact other than on the ENIAC, EDVAC, and IAS computer. War-related research took precedence for some years. George Stibitz, active in computers before the war at the BTL with Fry, thought it "strange" that wartime computing development got little support. After all, he reasoned, the need to do mathematical calculations drove the earlier civilian computer advances, and that need intensified with the crisis.[159] Actually, many improvements in prewar calculating machines came about to improve data handling, but Stibitz otherwise had a point. However, it was a question of priorities. Proximity fuses, atomic bombs, and acoustic mines had to be dealt with first. Most wartime work in computing circuitry was not in computers *per se* but in controls or test equipment for antiaircraft guns. The work of Atanasoff and Berry could easily have been overlooked in the confusion and press of activity, especially since there is not necessarily a straightforward connection between antiaircraft guns and computers, and since no paper had been published and no patent issued on the ABC.

When work in electronic digital computers began again in earnest, the ABC was in the dim past but still in working memory. Mauchly's failure to cite the ABC provides a case in point. Another example is that of Crawford, who wrote his thesis on antiaircraft gun controls and then became an advisor to Whirlwind. Historians of that project noted that Crawford and others involved,

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[155] Harold L Hazen, diary entry entitled, "Conversation with Dr. Thomas Johnson, Chief Physicist, Ballistic Research, Aberdeen," 14 April 1943. University of Pennsylvania.
[156] SHC (Samuel H. Caldwell), copy of memorandum to HLH (Harold L. Hazen), 23 October 1943. University of Pennsylvania.
[157] Thomas Johnson is quoted from a diary entry by Hazen, "Conversation with Dr. Thomas Johnson," 14 April 1943.
[158] Stern, *From ENIAC to UNIVAC*, 14.
[159] Stibitz, "Introduction to the Course on Electronic Digital Computers," 9-10.

"paid little heed to the historical background of the state of the art."[160] An English computer pioneer, Tom Kilburn, likewise recalled: "Computers were in the air; the subject was very exciting, and unfortunately one did not stop to record sources of information, but simply got on with the job."[161] In the heady excitement of building the early computers, crediting others got no thought. Crawford did mention in his thesis that others had "made a number of contributions" in electronic computation, but did not elaborate beyond noting that he understood little progress had been made.[162]

There is another less sanguine explanation for the ABC not attracting lasting official notice. The same reason may explain why Atanasoff did not get asked to work on digital computing projects earlier than the one for the NOL. As he and Berry labored on the ABC, Atanasoff began a second project at ISC for the NDRC that took priority for him and Berry. Atanasoff had been given the project by Warren Weaver, Director of Mathematical Analysis in Division 7, including subcommittee D-2, which developed antiaircraft gun directors. As noted, this was one area where digital devices had some application. Developed mechanisms tended to be electromechanical, although NCR, RCA, and Eastman Kodak explored electronic devices. However, the urgent priority was design and construction of analog mechanisms for tracking aircraft and predicting their future locations. Atanasoff was assigned to develop such a mechanism and given wide latitude.

As Atanasoff worked on the NDRC project, he and Weaver had a disagreement, and unfortunately, Weaver became extremely bitter over the incident and remained so for the years through the Honeywell trial. If Atanasoff hoped to do other computer work during the war, he made precisely the wrong enemy. Weaver then became Chief of the Applied Mathematics Panel (AMP) of the NDRC. Computing was part of the diverse responsibilities of the newly created AMP. Fry, Caldwell, and others who knew of the ABC worked for Weaver. Companies doing digital device development also tended to work with Weaver.[163] In effect, Atanasoff was blackballed from wartime computer-related projects. It was also unlikely that Weaver's supervision facilitated open consideration or attributing of ideas that came from Atanasoff. The University of Pennsylvania

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[160] Redmond and Smith, *Project Whirlwind*, 28.

[161] T. Kilburn, letter to N. Metropolis, 8 February 1972. Quoted in N. Metropolis and J. Worlton, "A Trilogy on Errors in the History of Computing," in *First USA-Japan Computer Conference Proceedings: October 3-5, 1972, Tokyo, Japan* (Montvale, New Jersey: American Federation of Information Processing Societies, 1975), 685.

[162] Crawford, "Automatic Control by Arithmetical Operations," 1.

[163] Rajchman, "Early Research on Computers at RCA," 465-467. Also, *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Summary of Testimony of Dr. Warren Weaver," 1-6. ISU, Parks, "Henry L. Hanson Papers" (box 5, folder 2).

began the ENIAC project independent of Weaver—another scientist who had originally favored the ABC but allegedly saw little value in the ENIAC[164]—but Mauchly did not encourage participation of Atanasoff either.[165] However, it must be noted that there is no evidence Atanasoff attempted to become involved in computers after the ABC. He left ISC for the NOL, where he immersed himself in acoustic science. Even his participation in the NOL computer project was not by choice, given the crush of his other duties.

The legacy of the ABC has therefore likely been significant but hidden in history. On the other hand, the impact of the ENIAC has been all too evident. The ENIAC did not provide precedence in technology, and better computers from private sources were coming along independently. Indeed, superior electronic circuit concepts existed before the war. It is probably true that only government would have built the ENIAC, because only it could afford to be so careless with money. The true legacy of the ENIAC has been that it gave impetus for extravagant and unnecessary government financing of research that continues to this day.

Historians of computers have been struck by how limited the future of computers appeared in the late 1940s. Extraordinary as it sounds, the pioneers may have thought that demand for computers could be completely satisfied by a handful of machines. Ten computers at most in the world were sufficient, according to some accounts. This has seemed a paradox: How could the brilliant men who created the computer not see more of its potential? Myriad uses are taken for granted even by children today, so why did people not grasp some of those possibilities upon the unveiling of the ENIAC? Historian Paul Ceruzzi identified three reasons why the utility of the computer went largely unrecognized in its initial years. As a first concern, scientists believed that any machine with so many vacuum tubes could never be reliable. However, vacuum tube failures turned out to be tolerable, because even the early computers worked so fast that they could on average do a lot of work between failures. Moreover, computer designers learned to incorporate conservative design principles that included redundant systems and check (and self-correction) mechanisms. Computers became error free for all practical purposes. A second reason for the lack of foresight had to do with the pioneers

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[164] *Honeywell*, "Transcript of Proceedings," 1,850; Stern, *From ENIAC to UNIVAC*, 71.
[165] Mauchly claimed he had asked Atanasoff in 1941 to join him at the University of Pennsylvania to build a computer. There is no record of that, but there is one of Mauchly asking to be allowed to build another ABC. John W. Mauchly, "The ENIAC," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 549; John W. Mauchly, letter to J. V. (Atanasoff), 30 September 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

themselves, principally an elite cadre of specialists. Narrowly focused, they built computers to solve problems in mathematics and did not foresee other uses. They did not yet grasp the ramifications of the power of digital computers for manipulating any symbol transformable to zeros and ones. Finally, no one understood how people would come to interact with computers. Before the monitor, mouse, and high-level languages, communicating in machine language with mathematical algorithms and paper cards was esoteric and labor intensive, not something for most people.

The analysis by Ceruzzi is trenchant but incomplete. There was also the issue of name, which he mentioned but did not explore fully. Before the ENIAC, the word computer occasionally denoted a machine, but often meant a human who solved mathematical problems with paper, pencil, and desktop calculating machine.[166] The Army employed people, mostly women, as computers to solve ballistics problems using more advanced algorithms than the ENIAC could handle.[167] Even so, the ENIAC was formally designated a computer to emphasize its supposed human-like capabilities. Other early computer builders were more humble. The EDSAC was a calculator by name, although recognized today as perhaps the first computer. IBM deliberately avoided the word computer for years, even for machines far more capable than the ENIAC. Its Selective Sequence Electronic Calculator, or SSEC, is a contender for title of first true computer. It was built independently of Eckert, Mauchly, and von Neumann but finished early in 1948. The IBM 701, modeled on the IAS computer for general use by the military, had the formal name Defense Calculator. The IBM 650 became the most popular computer of the 1950s. Some 2,000 were built as Magnetic Drum Calculators. Concerned for the sensibilities of its customers, IBM worried that the word computer evoked too great of emotions, conjuring up disquieting images of dark mysterious technology and people out of work, replaced by electronic brains.[168] No doubt the reluctance of IBM to call computers by that name is one reason that historians of computers regard the company as having been stodgy, hesitant of the new technology, when in fact it stayed close to the forefront.

The upshot of all this was that, until the UNIVAC, a computer (machine) popularly meant the ENIAC. That being the case, the question becomes obvious: Why would anyone think the world needed more computers (ENIACs)? Indeed, the world did not and built no more. Historians of

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[166] Ceruzzi, "An Unforeseen Revolution," 189-195. For an example of the word computer used before World War II to mean a person and then a machine, see Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 316 and 318. See also G. R. Stibitz, "Computer," 1940; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 248.
[167] Stern, *From ENIAC to UNIVAC*, 12.
[168] Pugh, *Building IBM*, 136, 143, 169-172, and 180-182.

computers have assumed that scientists who disapproved of the ENIAC were simply old fashioned. wedded to old technologies. On the contrary. scientists who thought like Caldwell. Hazen. and Weaver proved right: The ENIAC was outdated. impractical. and did not get finished in time to help with the war. The world did not require more computers when the word meant ENIAC. but it had urgent need for high quality. truly innovative. electronic computing machines. especially if they could be had for a reasonable price.[169] Businesses and government agencies snapped up such machines as they became available. even at high prices. Vendors were somewhat surprised but fully prepared to move cautiously toward more powerful computing machines. IBM. as a case in point. began designing electronic calculators in the early 1940s but had to put plans aside during the war. It then introduced electronic calculators into its product line. got an enthusiastic response. and needing no prodding from government. began designing electronic computers. Atanasoff. as a scientist. anticipated a future for computers commercially.[170] Writing to a tube manufacturer in 1940. he asserted. "If this machine (the ABC) is manufactured in any considerable number. the tube and condenser manufacturers stand to do a good business."[171] Atanasoff in fact expected the ABC. or rather commercial versions. to be built in large numbers. He did not plan to manufacture the computers himself but anticipated selling the right. and a number of corporations expressed interest.

There looks in retrospect to have been a natural evolution that led inevitably to computers. given progress in technology generally. impetus in information-processing specifically. and growing need for them by scientists. governments. and businesses. Moreover. those who assume computers

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[169] One computer pioneer alleged to have said that only a few machines were needed was Howard Aiken. famous for helping design the ASCC. an electromechanical computer completed in late 1942. Historian I. Bernard Cohen has noted that Aiken's remark must be put in context. According to Cohen. Aiken made his prediction in March 1949 as part of his involvement with Subcommittee Z. a committee put together by the National Research Council of the National Academy of Sciences to evaluate proposals for a post-ENIAC computer that the Census Bureau intended to purchase. Subcommittee Z thought all the proposals premature. Even so. Cohen believed the conclusion reflected "hostility" directed at Eckert and Mauchly by members of the subcommittee. including. besides Aiken. George Stibitz. Caldwell. and von Neumann. Thus. Aiken's remark referred to computers of the type proposed by Eckert and Mauchly. not computers generally. Cohen quotes Aiken as suggesting. "rather ought we to turn to assisting in the development of small. desk-sized computers." Aiken therefore actually believed there was a large need for computers. but that the production of big machines should wait. an arguably wise position considering the problems of producing the UNIVAC. the computer the Census Bureau bought. I. Bernard Cohen. *Howard Aiken: Portrait of a Computer Pioneer* (Cambridge. Massachusetts: MIT Press. 1999). 283-293.

[170] John V. Atanasoff. transcript of interview with Bonnie Kaplan. Smithsonian Institution. 10 August 1972. 8. Smithsonian.

[171] J. V. Atanasoff (unsigned). copy of letter to R. M. Bowie. Hygrade Sylvania Corporation. 19 June 1940. ISU. Parks. "John Vincent Atanasoff Papers" (box 23. folder 5).

could only have been developed by government, or big business, for that matter, misunderstand the circumstances of invention. Bureaucracy is its enemy. Telling is that only fifteen of the one hundred largest companies in 1917 survive today.[172] Through a process that economist Joseph Schumpeter termed "creative destruction," businesses spring to life as if from nowhere to create and exploit new technologies, and old, ossified corporations whither away, often to be absorbed into more aggressive companies.

The process is coldly evident even in the short history of electronic digital computers. There were twelve major U.S. producers of commercial computers a decade after World War II. Four remained by 1986, although numerous new ones emerged in the meantime.[173] Where today are NCR, DEC, or Sperry Rand, or any of dozens of formerly significant but now mostly defunct computer producers?[174] IBM has been an exception, and it has suffered notable stumbles. In fact, it is estimated that most innovation comes from industries in existence for no more than about ten years.[175] Corporations rise and fall on their ability to innovate, but government, the ultimate bureaucracy, grows regardless. Indeed, much growth in government in the twentieth century countered what had been considered flaws in capitalism. In smoothing the vicissitudes of the free market, however, governments may have also stifled its ability to create. The state is ordinarily the least likely entity to promote economically viable innovation, contrary to prevailing wisdom.

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[172] Editors of *Forbes*, "Steel versus Silicon," 130.

[173] Flamm, *Creating the Computer*, 81-82. See, "Table 4-1. Chief Producers of Digital Computers, 1954."

[174] To review and extend its story, the Eckert-Mauchly Computer Corporation became part of Remington Rand in 1950. Remington Rand merged with Sperry Corporation to become Sperry Rand in 1955. The company changed its name back to Sperry before merging with Burroughs Corporation in 1986. The organization survives as Unisys Corporation, now primarily a service company. AT&T bought NCR in 1991 and lost billions with it. NCR exists again as an independent company, focusing on such things as automatic tellers. Compaq bought DEC in 1998, but as of this writing is itself being acquired by Hewlett-Packard. "The New Computer Landscape," *The Wall Street Journal*, 6 September 2001, B1 and B8.

[175] "A Survey of Innovation in Industry," *The Economist*, 6.

CHAPTER 2. J. V. ATANASOFF: COMPUTER PIONEER

Historical emphasis on the ENIAC has popularized the notion that the existence of computers is due to Mauchly and Eckert and government sponsorship of research beginning with World War II. On the contrary, the ENIAC was the fruitless offshoot from a vigorous growth in information-handling technologies flourishing before the war thanks to private initiative and money. A full accounting for computers must include seminal inventions as far back as the early nineteenth century or before. The combined momentum of numerous efforts in the private sector was heading into true digital computers by 1940 and was only interrupted—temporarily—by war. No early project advanced more of what computers became than the ABC. Arguably, it ranks with the EDVAC and IAS computer as the machines that shaped modern computing.

Centering the history of early computers anew on the ABC highlights Atanasoff and Berry's achievement, all the more noteworthy for its likely impact on subsequent computers. It also helps shift focus to a long evolution of technologies leading into true computers. Furthermore, the story of the ABC illuminates factors that made the computer necessary, of which a requirement for ballistics tables is but one example. As a bonus for anyone interested in the fundamentals of computer design, the ABC included basic features still part of computers. Study of the ENIAC is less instructive, so different was it from computers today. Most important here, however, a broad history including the ABC illustrates that government funding had little true importance to the invention of the computer.

Of the ABC's two inventors, Berry got involved after Atanasoff. Berry refined the design and had responsibility for fabrication, including supervising the other students and craftsmen who did much of the work. However, Atanasoff conceived the ABC's underlying concepts and sketched out its overall design.[1] It is with him that a full and inclusive history of modern computing might therefore begin.

John Vincent Atanasoff was born into a lower middle-class family, at once unique, but with characteristics not untypical of the time. His mother, Iva Purdy Atanasoff, traced her ancestry to Jeremiah Purdy, who fought under George Washington in the Revolutionary War. She took normal training and taught at a rural school close to her parents' farm near Hamilton, New York. It was in Hamilton where she met her husband, an immigrant from Bulgaria named at birth Ivan Atanasov (no

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[1] J. V. Atanasoff, transcript of interview with B. Kaplan, Smithsonian Institution, 17 July 1972, 1-7. Smithsonian.

middle name).[2] Turkish soldiers had shot and killed his father, who died allegedly carrying him, a young child and apparently also wounded in the incident.[3] His mother remarried some years later and shipped the then thirteen-year-old Ivan to America with her brother.[4]

Ellis Island immigration officials changed the lad's name to John Atanasoff. His uncle had come to sell attar, or fragrant oil, and went back to Bulgaria two years later. He may have returned once.[5] The boy stayed and worked at menial jobs to put himself through the Peddie School for Boys in Hightstown, New Jersey. Upon advice from a Baptist minister, Ivan (now John) attended Colgate College (later University) in Hamilton, with intent of also becoming a Baptist minister.[6] Originally Greek Orthodox, he instead became a Methodist about the time he met his future wife, a Methodist, and went on to receive a Bachelor of Philosophy degree. His education at Colgate emphasized Latin and Greek but included basic science. He later became an electrical engineer on that foundation through correspondence courses and self-study. As much as this sounds the quintessential American success story, John Vincent (henceforth Atanasoff) believed his father's experiences as a youth caused him to feel "intense insecurity" the rest of his life.

Feelings of insecurity perhaps were a factor in frequent moves the Atanasoff family made, although tough economic circumstances provided a more immediate reason. Atanasoff was the eldest of ten children, eight of whom survived childhood. His parents had married about the time his father graduated from Colgate College. His father worked for, first, Edison Company and then the Utica Gas and Electric Company.[7] Atanasoff was born about that time on 4 October 1903 in his maternal grandparents' house near Hamilton. Several years and towns later, young Atanasoff began school in Lyndhurst, New Jersey, where his father had taken employment with the Delaware, Lackawanna and Western Railroad. Because members suffered respiratory problems, the family relocated to Osteen, Florida, when Atanasoff was eight. His father worked for Amalgamated Phosphate Company. Atanasoff moved around the area with his family four more times before graduating from high school in 1920 in Mulberry, Florida, at age sixteen and having completed eleven grades.

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[2] Clark R. Mollenhoff, *Atanasoff: Forgotten Father of the Computer* (Ames, Iowa: Iowa State University Press, 1988), 12.

[3] Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone, Paul Mobley, 30 June 1998.

[4] J. V. Atanasoff, New Market, Maryland, transcript of interview with Uta C. Merzbach, 5 May 1969, 6. Smithsonian.

[5] John Vincent Atanasoff, Monrovia, Maryland, transcript of tape-recorded interview with William R. Turner, 27 October 1986, 38-39. ISU, Parks, "John Vincent Atanasoff Papers" (box 20, folder 3).

[6] Mollenhoff, *Atanasoff*, 12-13.

[7] Atanasoff, interview with Merzbach, 5 May 1969, 1-6.

Atanasoff did not care for sports and had little opportunity to participate in extracurricular school activities, but he was a precocious and studious boy.[8] At an early age he took an avid interest in mathematics and science and loved reading books from his father's library. He began studying college algebra and the slide rule at about age ten.[9] His father supported his studies, but his mother had greater patience and helped more. Atanasoff mostly taught himself. He developed great powers of concentration and tolerance for drudgery. Late in life, he reflected that colleagues had credited him with having a superior intelligence that allowed him to learn anything easily. "It isn't true," he averred modestly, "It's just that I labor so intensely in the vineyard, but by myself." Atanasoff's intelligence unquestionably ran deep, but he spoke candidly in admitting that he had made the most of his mental gifts from an early age by laboring "almost continuously."[10]

Young Atanasoff stayed out of school to earn money for over a year between high school and college. Much of that time he worked on a crew prospecting for phosphate, living in makeshift camps in the Florida woods, and studying solid geometry at night by light of campfires.[11] He saved $530 by the fall of 1921 and entered the University of Florida at Gainesville.

Atanasoff had decided long before that he wanted to be a theoretical physicist. Physicists tended to be applications and experimentally oriented. By contrast, a theoretical physicist, or mathematical physicist, was as much mathematician as physicist. "It is an armchair profession," according to Atanasoff, "You do the job sitting in a preferably soft chair and thinking as hard as you can."[12] Atanasoff kept a large, comfortable armchair in his office at ISC for that purpose.[13]

The University of Florida did not offer theoretical physics as a major, so he selected electrical engineering as the most theoretical major available.[14] His default choice proved serendipitous,

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[8] *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Dr. John V. Atanasoff," 36, 39, 57, and 58. ISU, Parks, "John Vincent Atanasoff Papers" (box 29 folder 1).

[9] Mollenhoff, *Atanasoff*, 14.

[10] Atanasoff, interview with Merzbach, 5 May 1969, 16 and 56 (actually unnumbered).

[11] "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968. ISU, Parks, "John Vincent Atanasoff Papers" (box 27, folder 5).

[12] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 33 and 60-61; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Transcript of Proceedings," 1,624. ISU, Parks, "John Vincent Atanasoff Papers" (box 43).

[13] Charles J. Thorne, Camarillo, California, tape-recorded interview over the telephone with Paul Mobley, 2 April 1998.

[14] John Vincent Atanasoff, "Advent of Electronic Digital Computing," *Annals of the History of Computing* 6, no. 3 (July 1984), 231; John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 18 February 1972, 4-5. Smithsonian.

because the curriculum gave him, in addition to mathematics and theory of electricity, practical instruction that served him well through his career, notably in design of the ABC. He did not study electronics, but among his engineering courses were machine shop and foundry practices, drafting, and other hands-on classes. He also had a course in contract law.[15]

Atanasoff worked part time after his freshman year for money to continue his studies. His varied employment included waiting on tables in a college mess, helping in a storeroom, serving as a campus electrician, and surveying streetcar lines in Jacksonville, Florida. Most notably, he taught physics, chemistry, and general science in the Gainesville high school. A desperate principal, suddenly short an instructor, sought him out midway through his junior year. At first Atanasoff hesitated, remembering that teaching required a certificate. Undeterred, the principal told him that examinations for teachers were to be given in two days, and if he could pass three areas of concentration, the job was his. Atanasoff excused himself from classes, studied biology for the two days, took examinations in physics, agriculture, and biology, and easily passed all three. He taught school the remainder of his time at the University of Florida, even becoming "Head" of the high school science department. He nonetheless graduated on schedule in 1925 with a Bachelor of Science in electrical engineering and outstanding overall marks of 97.6 (out of 100).[16]

Atanasoff received offers of employment as an engineer, including one from the newly organized Bell Telephone Laboratories (BLT),[17] but he had his career goal set.[18] ISC responded first to his applications to graduate schools of mathematics as preparation to obtaining a Ph.D. degree in physics. The college offered him a teaching fellowship but demanded a commitment. Atanasoff accepted and then received other offers, including one from Harvard. True to his word, he began studies at ISC the next fall.[19] He also taught undergraduate mathematics half time for a stipend of $800 for the academic year.[20]

Atanasoff completed a Master's degree in August 1926 with a major in mathematics and minor in physics.[21] In his thesis he attempted to develop a theoretical explanation of the behavior of

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[15] Atanasoff, interview with Merzbach, 5 May 1969, 20-26 and 32-33.

[16] Atanasoff, interview with Merzbach, 5 May 1969, 34; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 63-69; "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968.

[17] Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Alfred A. Knopf, 1978), 188.

[18] "John Vincent Atanasoff Reference Chronology," compiled by Dorsey, Marquart, Windhorst, West & Halladay, circa 1968. ISU, Parks, "Clark Mollenhoff Papers, 1968-1990" (box 1, folder 27).

[19] Atanasoff, interview with Tropp, 18 February 1972, 7-8.

[20] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 80.

[21] Atanasoff, interview with Merzbach, 5 May 1969, 39.

gases that conformed better to experimental observations. He noted that all existing models were "wooden, unnatural affairs with no physical background."[22] As an alternative, Atanasoff expanded upon the virial of Clausius, a seldom used expression of kinetic energy which he learned reading English physicist J. H. Jeans's *The Dynamical Theory of Gases*. Rudolf Clausius, a nineteenth-century German, laid much of the foundation of thermodynamics. His virial accounted for the properties of gases by the statistical sum of forces of interaction and without considering molecular motion. Jeans downplayed the virial as giving inaccurate results,[23] but Atanasoff saw potential for it after he studied Clausius in original German.[24] Atanasoff tried to construct an improved mathematical model based on the virial, consistent with known atomic structure, and that satisfied the characteristics of a close-to-ideal gas such as neon or argon.[25] He did not succeed as well as he hoped but had the consolation of seeing his judgment confirmed when, with improved understanding of the atom due to developments in quantum mechanics, the virial evolved into a common tool for kinetic analysis of gases.[26] Jeans accepted applicability of the virial by 1940.[27] Atanasoff's thesis also helped prepare him for study in quantum mechanics, although his thesis did not include it.

Atanasoff stayed at ISC after graduation, working as a full-time instructor of mathematics for $1,800 per year. He read extensively on his own[28] and continued taking coursework that he hoped to apply toward a doctorate at another school.[29] ISC did not yet give doctorates in physics or mathematics. He also married Lura Meeks, three years his senior and originally from Quanah, Texas. Poor, hard working farmer-ranchers, the Meeks settled near Cheyenne, Oklahoma, still the rough frontier town. Lura taught for several years and saved money to study home economics and the arts. Independent and ambitious, she selected ISC because she understood that it had the best home economics program in the world. John and Lura met at Thanksgiving at the Dixie Club on campus

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[22] John V. Atanasoff, "On the Dynamics of a Certain Type of Molecule Possessing Spherical Symmetry," unpublished M.S. thesis, Iowa State College, Ames, Iowa, 1926, 8.
[23] J. H. Jeans, *The Dynamical Theory of Gases* (London: Cambridge University Press, 1904), 143-148.
[24] Atanasoff, interview with Merzbach, 5 May 1969, 42.
[25] Atanasoff, "On the Dynamics of a Certain Type of Molecule Possessing Spherical Symmetry," 8-9 and 33.
[26] Atanasoff, interview with Merzbach, 5 May 1969, 41-42; Atanasoff, interview with Tropp, 18 February 1972, 8-9; Atanasoff, interview with Kaplan, 17 July 1972, 26-27; J. V. Atanasoff, New Market, Maryland, interview with B. Kaplan, 23 August 1972, 17-19. Smithsonian.
[27] James Jeans, *An Introduction to the Kinetic Theory of Gases* (New York: Macmillan Company, 1940), 69-77.
[28] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 87-88.
[29] Atanasoff, interview with Merzbach, 5 May 1969, 39; Atanasoff, interview with Kaplan, 17 July 1972, 30; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 84-87.

and married the following June. The couple faced an early crisis when she left to fulfill a commitment made before their engagement to teach the 1926-1927 school year in Montana. She had taken the job to earn money to finish her education. Halfway through the school year, begged by her husband, Lura returned to Ames.[30] She then finished her degree.[31]

It was a heady time to study physics, that March 1929, when Atanasoff and family, now including daughter Elsie, moved to Madison, Wisconsin, for him to complete a doctorate at the University of Wisconsin. Physics reverberated with excitement still over Albert Einstein's theories of relativity. A field of study with even more profound implications had coalesced less than two years earlier. In October 1927, the world's most distinguished physicists had gathered at the Solvay conference in Brussels to agonize over a growing accumulation of bewildering propositions in quantum mechanics. The debate at Solvay formalized an extraordinary overall formulation known as the Copenhagen interpretation. Skeptics abounded, including Einstein, but even he had to finally accept the peculiar logic of the new branch of physics. Key contributors included such European intellectual giants as Arnold Sommerfeld, Louis de Broglie, Paul A. M. Dirac, Wolfgang Pauli, and Erwin Schrödinger. Max Born, Werner Heisenberg, and, especially, Neils Bohr contributed most to the Copenhagen formulation.[32] Bohr headed an institute of physics in Copenhagen; hence, the name for the theory.

Quantum mechanics is said to be concerned with explaining physical phenomena at the minute size of molecules or smaller. Since its effects can involve large distances, light years even, quantum mechanics more fundamentally can be defined as that area of physics dealing with extremely small changes of energy at the atomic level.[33] Perhaps to his regret, Einstein played a major role in stimulating creation of quantum mechanics by suggesting in 1905, the same year he postulated special relativity, that light sometimes acts more like particles, or quanta, than waves. A

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[30] Gather, interview with Mobley, 30 June 1998; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Lura Atanasoff," 4. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 8, folder "Dep-Lura").

[31] A more serious situation occurred when Atanasoff suffered what has been described as a nervous breakdown, although exhaustion seems more probable, the result of his driving himself so hard. He sought treatment as an outpatient but did not stop working. "John Vincent Atanasoff Reference Chronology," 6; J. V. Atanasoff, II, Boulder, Colorado, tape-recorded telephone interview with Paul Mobley, 21 July 1998.

[32] Kevles, *The Physicists*, 159-168.

[33] Roger Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics* (New York: Oxford University Press, 1989), 237.

specific example was that of the photoelectric effect, or the emission of electrons from the surface of a metal due to impingement of light. Quanta of light and other radiation came to be called photons. American Robert A. Millikan confirmed Einstein's quantum model for the photoelectric effect by 1916. Even so, few physicists thought the idea credible until an exasperated Arthur Compton, another American, having no more plausible explanation, embraced quantum energy in 1922 as a means to describe X-ray scattering upon impact with metals. De Broglie turned Einstein on his head in a 1924 dissertation in which he conjectured that particles of matter could also behave like waves.

Einstein by then had become a major scientific figure. Observations made during a solar eclipse in 1919 indicated that light from stars bent slightly as it passed near the sun and confirmed general relativity, which he had articulated in 1916. Einstein then won a Nobel Prize in 1921 for his work on the photoelectric effect. His stature had become such that when he accepted de Broglie's thesis, others reluctantly did too.[34]

The initial primitive formulation of the radical new science came in 1925 from Heisenberg, who developed an algebraic framework using matrices for calculating values of the intensities and frequencies of the spectral lines of light.[35] Schrödinger took the idea of wave-particle duality the following year and formulated wave mechanics, in which the characteristics of atoms and photons were expressed as wave equations. Born interpreted the square of the solution of a wave equation to be the statistical probability of a subatomic particle being found at a particular location at a given time. The bizarre implication was that a particle only becomes a point in space once a measurement is made to locate it. Schrödinger demonstrated the equivalence of his wave mechanics with Heisenberg's matrix mechanics, and Dirac shouldered much of the burden of subsuming both into a general theory. Dirac also combined quantum mechanics with special relativity to better explain the spin of electrons.[36] Based on the implications of Born's interpretation of wave equations, Heisenberg enunciated the principle of uncertainty, which stated that it is impossible to calculate simultaneously and accurately both location and velocity of a subatomic particle. Bohr built on uncertainty with a principle of complementarity, which proposed that at the quantum level complete descriptions required mutually exclusive but complementary concepts: waves and particles, for example, or position and velocity.

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[34] Kevles, *The Physicists*, 85-86, 157-159, and 163-164.
[35] Linus Pauling and E. Bright Wilson, *Introduction to Quantum Mechanics: With Applications to Chemistry* (New York: McGraw-Hill, 1935), 48. Atanasoff used this text by Pauling and Wilson in introductory quantum mechanics courses he taught.
[36] Penrose, *The Emperor's New Mind*, 153.

The Copenhagen interpretation amounted to the greatest upheaval in the physical understanding of the universe since Isaac Newton postulated gravity. Where classical physics, even relativity, depicted the world as continuous and causally predictive, the new quantum mechanics, at least at its deepest level, had it to be discontinuous, indeterminate, and statistical. Applications of quantum mechanics accordingly demanded employment of mathematics of great sophistication. Furthermore, physics became more mathematical overall.

Herman Goldstine observed that physicists expended most their theoretical efforts explaining the world qualitatively until the late 1920s.[37] They visualized concepts in ideal terms that could be articulated with relatively simple mathematical expressions. Emphasis shifted to the quantitative coincident with the Copenhagen interpretation. As Atanasoff put it, with quantum mechanics a whole range of problems for the first time "became understandable and capable of solution," at least for those who managed to master the mathematics.[38] In their excitement, physicists began to put even classical physics on a more rigorous mathematical foundation.[39] Many of the old guard fell by the wayside intellectually, unwilling or unable to make the transition.[40] Atanasoff was fortunate in finding at the University of Wisconsin a number of outstanding instructors, but in particular, theoretical physicists in touch with the revolutionary and increasingly mathematically, and statistically, oriented thinking from Europe.

One of Atanasoff's professors was J. H. Van Vleck, a young man about four years older than he. Van Vleck had a curious hobby of memorizing passenger train schedules, a hobby he acquired when ill as a boy on a trip to Italy with his parents. While confined to bed, he put to memory timetables for all Italian trains.[41] His wealthy and well-connected father later gave him a fat volume of tables for trains in America as a Christmas present. When Atanasoff knew him, Van Vleck gave upon request current schedules off the top of his head for trains between any two stops in the U.S.[42]

Van Vleck might have distinguished himself as a travel agent, but he also had considerable aptitude in physics. He earned a Ph.D. degree at Harvard in 1920 with a dissertation on the ionization

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37 Besides helping develop early computers, Goldstine wrote extensively on the history of applied mathematics and computers.

38 John V. Atanasoff (attributed), "What is the Quantum Theory," circa 1940, 9. ISU, Parks, "John Vincent Atanasoff Papers" (box 9, folder 5).

39 Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, New Jersey: Princeton University Press, 1972), 34 and 102.

40 Kevles, *The Physicists*, 159-169.

41 Frederick Fellows, "Van Vleck, John Hasbrouck," in *Dictionary of Scientific Biography*, Supplement II, 1990.

42 Atanasoff, interview with Merzbach, 5 May 1969, 53-54 (actually unnumbered).

energy of the "cross-orbit" model of the helium atom. Bohr had suggested the topic in part, and the resulting dissertation was the first purely theoretical one in the U.S. Van Vleck left Harvard to teach at the University of Minnesota, where he secured his reputation with publication of *Quantum Principles and Line Spectra* in 1926.[43] The state of affairs prompted Van Vleck to lament that physicists had been forced into "contortions" attempting, "to explain the simultaneous appearance of quantum and classical phenomena." He consoled himself with the belief that, "paradoxical theories are required to explain paradoxical phenomena."[44] Van Vleck's monograph was regarded as authoritative,[45] but Heisenberg and Schrödinger had in fact already rendered his conclusions archaic.[46] To his credit, Van Vleck strove to stay abreast of the whirl of activity in Europe. Walter Brattain, a student in Minnesota and future co-inventor of the transistor, recalled that, "quantum mechanics was changing so fast that every student audited Van Vleck's course every year."[47]

Van Vleck accepted a position at the University of Wisconsin early in 1928, in part because it had instituted a program of hosting a theorist from Europe for a semester each year.[48] Atanasoff therefore had the great luck his first semester at Wisconsin of attending lectures by both Van Vleck and Dirac.[49] However, he got off to a rocky start with Van Vleck, who disliked that Atanasoff insisted on entering mid-term. ISC was on the quarter system, so end of winter quarter at ISC in March was halfway through spring semester at the University of Wisconsin. Atanasoff refused to be intimidated but nonetheless despaired of the situation. Despite having attended but one-quarter of the sessions in the notoriously difficult two-semester class, he was one of five out of about twenty-five students willing to attempt the final exam. He received a high score in Van Vleck's quantum mechanics, as he typically did in all his classes.[50]

Interestingly, Van Vleck also taught quantum mechanics to another of the three primary inventors of the transistor. John Bardeen likely was in the same class at Wisconsin with Atanasoff that spring and certainly attended the guest lectures by Dirac, who made such an impression on him

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43 Fellows, "Van Vleck," *Dictionary of Scientific Biography*.
44 John H. Van Vleck, *Quantum Principles and Line Spectra* in *Bulletin of the National Research Council* 10, no. 54 (March 1926), 287.
45 Kevles, *The Physicists*, 197.
46 Fellows, "Van Vleck," *Dictionary of Scientific Biography*.
47 Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W. W. Norton, 1997), 51-52.
48 Fellows, "Van Vleck," *Dictionary of Scientific Biography*.
49 Atanasoff, interview with Merzbach, 5 May 1969, 54-55 (actually unnumbered).
50 Atanasoff, interview with Turner, 27 October 1986, 58; Mollenhoff, *Atanasoff*, 25-26; Atanasoff, interview with Merzbach, 5 May 1969, 45-46; Atanasoff, interview with Tropp, 18 February 1972, 14-15.

that he changed his major. Bardeen eventually got a doctorate in physics at Princeton, but in 1929 he was a graduate student in electrical engineering at the University of Wisconsin and taking electives in physics.[51] As further crossing of paths, in 1941 Bardeen went to work for the NOL near Washington, D.C., doing research related to mines, although not involving acoustic science.[52] Atanasoff and Bardeen collaborated only indirectly at the NOL,[53] but Atanasoff did express disappointment that he had not been the one to invent the transistor. His interests in quantum mechanics and crystals made that not a farfetched possibility. According to Atanasoff, he had the "very kernel and heart of the transistor" right before his eyes, and "wondered about it and spent hours on it," but neglected to pursue it fully.[54]

Atanasoff's relationship with Van Vleck improved over the summer, when Atanasoff took a class on magnetic susceptibility from him.[55] Roughly that area of research led to Van Vleck sharing the Nobel Prize in 1977 with two other physicists.[56] Atanasoff also began his dissertation under Van Vleck. American physicists, including those who considered themselves theoretical, had particular interests in the late 1920s in applications of the pure theory emanating largely from Europe.[57] Atanasoff chose in like fashion to explore the effects of an electrical field on the helium atom, a topic suggested by Van Vleck.[58] Van Vleck then left for Europe to study developments in physics. Atanasoff became anxious when Van Vleck scheduled a meeting with all his graduate students for simultaneous final discussions of their work. He had a difficult topic and wanted his advisor's full attention one last time. Surmising his concern, Van Vleck told him not to worry, no one else would come to the meeting. Sure enough, none of the other students did, confirming Atanasoff's suspicion that he was not the only student who found Van Vleck a difficult mentor.[59]

The University of Wisconsin obtained the services of Gregor Wentzel in the absence of Van Vleck. Wentzel, a German, had studied at the University of Munich under Sommerfeld and continued postgraduate work with him, particularly on interpretation of atomic spectra. Wentzel had posts at the Universities of Leipzig and Zurich before his year at the University of Wisconsin.[60]

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[51] Besides the Nobel Prize in physics that Bardeen shared in 1956 with Shockley and Brattain for the transistor, Bardeen shared another Nobel Prize in physics in 1972 for work in superconductors.
[52] Riordan and Hoddeson, *Crystal Fire*, 77 and 118-119.
[53] Atanasoff, interview with Turner, 27 and 28 October 1986, 61, 64, and 73.
[54] Atanasoff, interview with Kaplan, 17 July 1972, 29.
[55] Atanasoff, interview with Merzbach, 5 May 1969, 46.
[56] Fellows, "Van Vleck," *Dictionary of Scientific Biography*.
[57] Riordan and Hoddeson, *Crystal Fire*, 74.
[58] Atanasoff, interview with Tropp, 18 February 1972, 16-17.
[59] Atanasoff, interview with Merzbach, 5 May 1969, 49-50.
[60] S. S. Schweber, "Wentzel, Gregor," *Dictionary of Scientific Biography*, Supplement II, 1990.

Atanasoff recalled that Wentzel had just gotten married and looked at his time in Wisconsin as something of a honeymoon. He had a poor command of English, so Atanasoff occasionally served as his translator.[61] Wentzel is best remembered as one of the formulators of the Wentzel-Kramers-Brillouin (WKB) approximation method used in certain situations to solve the Schrödinger wave equation.[62] Atanasoff found him congenial and felt fortunate to have the guidance of a distinguished theorist fresh from Europe.[63]

Atanasoff's dissertation entailed solution of the Schrödinger wave equation for helium perturbed by an electric field. The Schrödinger wave equation in basic form is a simple partial differential equation describing the wave functions of subatomic particles over time. A differential equation is one containing one or more derivatives, where a derivative relates the rate of change of one variable with respect to another. An ordinary (or total) differential equation contains a single independent variable; a partial differential equation contains two or more. In either case, few differential equations outside of textbooks have solutions that can be found analytically. Rather, differential equations often are solvable only indirectly and imprecisely by laborious approximation methods. Applications of the Schrödinger wave equation are of the latter sort, except for hydrogen, the simplest atom, and then only in ideal cases and in the absence of external fields, or perturbations. Furthermore, approximate solutions to the Schrödinger wave equation often evolved to solutions of systems of linear algebraic equations. This was frequently done by a technique of separation of variables, which led to combinations of an infinite number of solutions.[64] The accuracy of the final answer depended on the number of terms and how they were defined. On the other hand, solution of a problem in quantum mechanics through alternate use of matrix mechanics necessarily meant solving simultaneous algebraic equations.[65]

Extensive calculations had been completed on hydrogen by the time Atanasoff began his dissertation. As the next least complex atom, helium had come under heavy attack. Egil Andersen Hylleraas, a Norwegian and protege of Born, accomplished impressive pioneering work calculating the ground state of helium. The ground state of an atom is its condition of lowest energy.[66] The approximation method Hylleraas developed was particularly important for several reasons. First, it

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[61] Atanasoff, interview with Merzbach, 5 May 1969, 51-52 (actually unnumbered).
[62] David J. Griffiths, *Introduction to Quantum Mechanics* (Englewood Cliffs, New Jersey: Prentice Hall, 1995), 274.
[63] Atanasoff, interview with Merzbach, 5 May 1969, 52 (actually unnumbered).
[64] Griffiths, *Introduction to Quantum Mechanics*, 20-24.
[65] Pauling and Wilson, *Introduction to Quantum Mechanics*, 112-151, 165-175, 186-188, and 416-418.
[66] Griffiths, *Introduction to Quantum Mechanics*, 26.

gave good results compared to values measured experimentally. Second, the method had wide applicability. Finally, Hylleraas made extensive use of a calculator, probably for the first time in physics.[67]

Atanasoff's problem involved perturbation theory, in which an approximate solution was found in a perturbed state by building on that in the unperturbed case.[68] Atanasoff thus took the work of Hylleraas as his starting point for the more complicated problem he faced calculating the dielectric constant of helium. Deriving an extension, he obtained a result about 5 percent below the accepted experimental value; with further work, he managed a solution with about 2 percent error.[69] That compared favorably with results of other researchers doing similar types of calculations,[70] and Atanasoff published an abbreviated version of his dissertation in *The Physical Review*.[71] Like Hylleraas, Atanasoff used a desktop calculator to make his calculations. The experience of spending weeks manipulating a mechanical calculator was what "ultimately motivated" him to invent the electronic digital computer.[72]

The University of Wisconsin accepted Atanasoff's transfer credits from ISC and required minimal additional coursework. Atanasoff also had to pass a reading proficiency examination in French, which he managed after two weeks intensive study despite having little of the language previously. The examiner commented on his odd reading of French,[73] but Atanasoff could thus graduate after completing his dissertation at end of summer 1930.

Warren Weaver stood with Atanasoff at the ceremony in the absence of Van Vleck.[74] Weaver was a native of Wisconsin and son of a druggist. An unhappy boy with few friends, too small to pass a military physical during World War I, he found his calling as a teacher. He had earned a B.S. degree in civil engineering (1916) and doctorate in mathematical physics (1921) from the University of Wisconsin. After a short stint at the newly opened California Institute of

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[67] Per Stromholm, "Hylleraas, Egil Andersen" in *Dictionary of Scientific Biography*, 1972; Goldstine, *The Computer from Pascal to von Neumann*, 102-105.
[68] Griffiths, *Introduction to Quantum Mechanics*, 221.
[69] Atanasoff, "Advent of Electronic Digital Computing," 232.
[70] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 94-95; Pauling and Wilson, *Introduction to Quantum Mechanics*, 228.
[71] J. V. Atanasoff, "The Dielectric Constant of Helium," *The Physical Review* 36, no. 7 (1 October 1930), 1,232-1,242.
[72] Atanasoff, "Advent of Electronic Digital Computing," 232; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 99-102.
[73] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 78; Atanasoff, interview with Tropp, 18 February 1972, 15-16; Atanasoff, interview with Merzbach, 5 May 1969, 35.
[74] Atanasoff, interview with Merzbach, 5 May 1969, 48.

Technology (Caltech) working for Millikan. Weaver returned to Wisconsin and had become chairman of the Department of Mathematics by the time Atanasoff met him. Weaver disliked quantum mechanics as incompatible with electromechanical theory; rather, he made his name in classical physics by publishing *The Electromagnetic Field* with Max Mason in 1929. The book became a standard text for graduate students.[75] Weaver is better remembered for *The Mathematical Theory of Communication*, written with Claude Shannon and published in 1949.[76] The book was a seminal study in information theory, which has grown concurrently with digital technology and deals with how information is reliably measured, stored, and transmitted. Atanasoff had taken two classes from Weaver, including electrodynamics,[77] and served under him as an instructor of mathematics from fall 1929 until he graduated.[78] Atanasoff liked Weaver,[79] even if Weaver came to detest him.

Many freshly minted physics Ph.D.'s in 1930 applied for coveted postdoctoral fellowships to continue studies in Europe or, increasingly, at one of the four or five universities in the United States with greatest prestige. The lucky recipients incurred few responsibilities but could pursue their own research for up to two years while working under the tutelage of renowned physicists. The fellowships were privately funded, fairly plentiful, but awarded on merit. The National Research Council and the John Simon Guggenheim Foundation gave most of them.[80] As a top student of top professors and with a successful dissertation, and highly ambitious to boot, Atanasoff certainly could have been expected to apply for, and win, one of the fellowships. There is no evidence that he applied, however. He returned to Ames instead to take a position as an Assistant Professor of Mathematics. The reason may simply have been that he had a leave of absence from ISC and an

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[75] Warren Weaver, *Scene of Change: A Lifetime in American Science* (New York: Charles Scribner's Sons, 1970), 1, 11, 33, 55, 57, and 209.

[76] More precisely, Claude Shannon published "The Mathematical Theory of Communication" in the *Bell System Technical Journal* in 1948. The next year, that article and one by Weaver, "Recent Contributions to the Mathematical Theory of Communications," were published together as *The Mathematical Theory of Communications*.

[77] Atanasoff, interview with Tropp, 18 February 1972, 15.

[78] Atanasoff, interview with Kaplan, 23 August 1972, 86; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 96-97.

[79] *Honeywell*, "Transcript of Proceedings," 2,737-2,738.

[80] The National Research Council was created in 1916 to organize scientists for "the national service and welfare" during World War I. The NRC served government but was privately funded. The NRC became permanent, and in 1919, the Rockefeller Foundation began giving the NRC money for postdoctoral fellowships in physics and chemistry. Mathematics was added in 1923. Kevles, *The Physicists*, 111-112, 117-118, 149-150, 197-199, and 219-220.

obligation to return. Doubtlessly more important, Atanasoff had to support his growing family, made more difficult by the Depression.

What makes Atanasoff's decision to return to ISC nonetheless surprising was his ambivalent attitude toward the school. At least in darker moments, he regarded it as a "second-rate institution"[81] and the Midwest as "staid."[82] In the former opinion he was unfairly harsh if he meant the school as a whole. ISC, officially Iowa State College of Agriculture and Mechanic Arts, had a clear sense of mission as a land-grant college, focusing on engineering, home economics, industrial science, veterinary medicine, and above all, agriculture. It conferred its first Ph.D. in 1916 and ranked thirteenth in the nation in number of doctorates given in 1932. ISC had awarded 636 doctorates by 1942 in fourteen major fields, many related to agriculture or biological sciences. Over one-third (221) was in one major area, chemistry, but generally in sub-fields associated with agriculture and biology.[83] Likewise, chemical engineering at ISC had achieved international recognition exploring commercial uses for agricultural wastes.[84] In entomology, genetics, bacteriology, soil science, animal nutrition, plant pathology, botany, civil engineering, chemistry, and chemical engineering, ISC had a solid reputation.[85]

On the other hand, physics and mathematics at ISC were regarded as support to engineering and industrial science (and, of course, agriculture). More to the point, under pressure from the Iowa Board of Education to restrain expenses and school rivalry, the foremost planning objective in graduate studies at ISC was to avoid duplication of programs with the State University of Iowa (now University of Iowa), particularly in basic sciences.[86] Chemistry proved an exception. It had been expanding since 1913 under the dynamic leadership of agricultural chemist Winfred F. Coover.[87] Biology was another exception, but it was not politic for ISC to attempt much in mathematics and

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81 Atanasoff, interview with Merzbach, 5 May 1969, 45.
82 Atanasoff, "Advent of Electronic Digital Computing," 230.
83 Earle D. Ross, *A History of the Iowa State College of Agriculture and Mechanic Arts* (Ames, Iowa: Iowa State College Press, 1942), 356; R. M. Hughes (attributed), President Emeritus Iowa State College, "The Graduate School at Iowa State College," unpublished report, circa 1942, 1-3. ISU, Parks, "Vice-President for Research, Graduate College" (box 2, folder entitled "Historical Studies").
84 Alan I. Marcus and Erik Lokensgard, "The Chemical Engineers of Iowa State College: Transforming Agricultural Wastes and an Institution, 1920-1940," *The Annals of Iowa* 48, nos. 3 and 4 (Winter/Spring 1986), 177-205.
85 Ross, *A History of the Iowa State College*, 360.
86 R. E. Buchanan, "Graduate College" in *Twenty-Year Development Program*, unpublished report, Iowa State College, Ames, Iowa, September 1935, 31; Ross, *A History of the Iowa State College*, 294-301 and 330-333.
87 Harry J. Svec, *History of the Iowa State Chemistry Department*, unpublished manuscript, Ames, Iowa, 1998, chapter 7.

physics because of relatively strong departments at the State University. Therefore, research at ISC in physics stressed areas with "economics utilization" potential.[88] The physics faculty during the 1930s could boast of published papers exemplified by the following: "The lighting of a home under various color conditions" (1932), "Practical physics for agriculturists" (1935), "Thermal conductivity of stored oats with different moisture content" (1935), "The electrical conductivity of cod liver oil" (1937), and "Measurement of the viscosity of eggs by the use of a torsion pendulum" (1937).[89] Atanasoff published the latter paper.

To jump ahead a moment, World War II dramatically changed ISC, as it did the nation. Like Atanasoff, some faculty and staff departed during the war. For example, Gerald W. Fox had joined the physics faculty as an associate professor the same year that Atanasoff came back as an assistant professor. Fox left to help at the deliberately misnamed (for security reasons) Radiation Laboratory at MIT developing radar, but as an administrator and not a physicist. He later served for several months as a scientific advisor on the staff of General MacArthur in Japan.[90] He returned to ISC in 1947 and became head of the physics department after Atanasoff refused the position.[91]

The department was transformed under Fox, but largely thanks to Frank Spedding, a highly capable and strong-willed physical chemist specializing in rare-earth elements. Spedding had responsibility for a massive effort at ISC to provide uranium to the Manhattan Project. After first discovering a practical refining process, Spedding and his group produced about 2 million pounds of uranium metal from ore. The purified uranium went to facilities at Chicago or Oak Ridge, Tennessee, for processing into component isotopes.[92] The Ames Project, as it was called, also conducted basic research into uranium and related elements.[93] Federal money continued to surge into ISC after the war, not least because Spedding and ISC successfully sought establishment of a permanent Atomic Energy Commission laboratory (Ames Laboratory) on campus. Theoretical physics fit into Spedding's research plans, so he splashed money into the physics department. That allowed the

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88 Buchanan, *Twenty-Year Development Program*, 38.

89 Iowa State College Library, *List of Publications of Members of the Staffs of Iowa State College* (Ames, Iowa: Iowa State College, 1932-1937).

90 Daniel Zaffarano, Ames, Iowa, interview with Paul Mobley, 8 December 1997; ISC news release, "Dr. Fox to Head ISC Physics Department," 3 July 1947. ISU, Parks, "College of Science and Humanities, Department of Physics, Department Chairperson."

91 J. V. Atanasoff, New Market, Maryland, transcript of interview with B. Kaplan, 28 August 1972,14. Smithsonian.

92 Svec, *History of the Iowa State Chemistry Department*, chapter 8.

93 Carolyn Stilts Payne, "The Ames Project: Administering Classified Research as Part of the Manhattan Project at Iowa State College, 1942-1945," unpublished dissertation, Iowa State University, Ames, Iowa, 1992, 71.

department to install a 70 million electron volt synchrotron. A synchrotron is an apparatus designed to permit the study of subatomic particles by accelerating them to high speeds. Fox brought in new blood to strengthen the department and use the synchrotron.[94] Theoretical physics had thus arrived at ISC in a big way. Infusion of government money similarly transformed universities across the nation.

ISC eventually implemented a program in theoretical physics, but it was not prewar the best institution for someone with Atanasoff's interests. As late as 1942, Raymond M. Hughes, President Emeritus, declared categorically that ISC offered no graduate work in theoretical physics, rather, "doctoral work has been confined to applied physics."[95] Graduate students in physics did projects in fact that could be considered theoretical, but it is understandable that, as the only theoretical physicist at ISC, Atanasoff sometimes felt "very lonesome."[96] He had no doubt upon his return from Wisconsin that he could compete technically with the rest of the faculty, but he had not remembered the mathematics and physics departments being so distressingly "old-fashioned." The established members of the physics faculty had little understanding of advanced mathematics, and most had tentative grasp of the calculus, to Atanasoff's keen disappointment. Furthermore, to his thinking at least, there was too little research, and it of mediocre quality. He judged the mathematics department also in need of improvement, with that faculty failing to do justice to applications of mathematics.

Looking back from old age, Atanasoff recollected that the austere circumstances of the Depression colliding with his ambition had colored his opinions, and that he was happy at ISC overall. If the faculty refused to mandate the teaching of undergraduate physics using the calculus, it at least gave him considerable freedom to teach what and how he wanted.[97] Atanasoff may have paid a price for independence, however, because judging from reports that ISC presidents made periodically to the Board of Education, he received little recognition. The reports listed brief news items of interest. Atanasoff's name rarely appeared in the reports; others in the mathematics and physics departments made it occasionally.

Fox, who Atanasoff regarded as his chief rival at ISC, won frequent plaudits. For example, Hughes reported in 1933 that Fox and his students built a 400-watt "radio-phone" to communicate with a polar expedition.[98] Later Fox designed classroom hearing aids for students hard of hearing,

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[94] Daniel Zaffarano, Ames, Iowa, interview with Paul Mobley, 15 December 1997.
[95] Hughes, "The Graduate School at Iowa State College," 4.
[96] Atanasoff, interview with Tropp, 18 February 1972, 2.
[97] Atanasoff, interview with Merzbach, 5 May 1969, 89-90 (actually unnumbered); Atanasoff, interview with Kaplan, 23 August 1972, 83-85 and 87; John V. Atanasoff, transcript of interview with Bonnie Kaplan, Smithsonian Institution, 10 August 1972, 32. Smithsonian.
[98] R. M. Hughes, President ISC, report to (Iowa) Board of Education, 7 December 1933, 10. ISC, Parks, "President R. M. Hughes" (box 1, folder 2).

and that was duly noted.[99] After Fox toured Eastern universities, it pleased Hughes to convey Fox's impression that ISC was, "doing just as good work in our particular fields at a very small cost to the institution as compared with the older universities."[100] Fox managed to stay in tune with the college administration, but he also accomplished quality research. The physics department emphasized crystal research,[101] and Fox spent several months in late 1934 with Linus Pauling at Caltech. Pauling, a chemist and, eventually, two-time Nobel Prize winner,[102] earned his early reputation in X-ray analysis of crystals, one of Fox's research sub-fields. Pauling came to ISC the following spring to deliver a series of lectures.[103] Fox published more than anyone in physics did, and Hughes judged him in 1946 to be best known nationally of that faculty (Atanasoff was not considered).[104] In fairness to Atanasoff and Hughes, Atanasoff did copious amounts of worthy research, but it did not lend itself to news briefs of general interest.

Atanasoff evoked strong emotions from people. Most found him approachable and amiable, but upon further exposure, sometimes overwhelming and domineering. His self-confidence, frank honesty, and unconventional opinions offended some, but he left others, particularly subordinates and those with whom he worked closely, awestruck by his brilliance. He found it difficult to talk on subjects he thought frivolous and had an annoying tendency to bluntly curtail a conversation once it ceased to interest him.[105] If not in contemplation, then he was in frenetic motion, and he rarely hesitated to speak his mind. Furthermore, Atanasoff loved animated debate, especially those infrequent occasions when someone bested him in an argument.[106]

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[99] Charles E. Friley, President ISC, report to (Iowa) Board of Education, 18 November 1935, 3. ISC, Parks, "President Charles E. Friley " (box 1, folder 1).
[100] R. M. Hughes, President ISC, report to (Iowa) Board of Education, 9 May 1934, 7. ISC, Parks, "President R. M. Hughes" (box 1, folder 3).
[101] J. V. Atanasoff, copies of letters to Jay W. Woodrow, Head of Physics, 9 January 1935 and 10 January 1935. ISU, Parks, "John Vincent Atanasoff Papers" (box 9, folder 7).
[102] Pauling won the Nobel Prize in chemistry in 1954 and Peace Prize in 1962.
[103] R. M. Hughes, President ISC, reports to (Iowa) Board of Education, 12 November1934, 14; 14 February 1935, 7; and 4 May 1935, 12. ISC, Parks, "President R. M. Hughes" (box 1, folders 3 and 4).
[104] R. M. Hughes, President Emeritus ISC (attributed), "An Examination of the Research Staff of Iowa State College," circa 1946, 16 (in the second part of the report). ISC, Parks, "President R. M. Hughes" box 1, folder 9).
[105] Robert M. Stewart, Ames, Iowa, tape-recorded interview with Paul Mobley, 14 and 18 November 1997.
[106] Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone, Paul Mobley, 1 July 1998.

Atanasoff's independence of thinking fostered creativity and had other positive aspects, even as he ruffled feathers. As a minor but telling example, a student from Idaho, Philip J. Hart, belonged to the Church of Jesus Christ of Latter Day Saints (Mormons) and found many people he met in Ames (which, truth be told, was rather staid) did not accept him because of it. Atanasoff, an agnostic, listened with an open mind.[107] He became so intrigued that he purchased books on the Mormons and became expert on that topic, as on many others.[108] Thereafter, he rose in scholarly defense of Mormons whenever he heard them criticized without sufficient regard to facts.[109]

Atanasoff believed he raised more eyebrows over his political leanings. He claimed an inclination toward socialism from birth, although that did not stop him from creating a corporation in the early 1950s to improve proximity fuses. He later diversified his company, The Ordnance Engineering Corporation, into non-defense areas. Atanasoff also had a string of shrewd real estate and other financial investments. The sum of his business activities left him comfortably situated, but he seemed little troubled by any inconsistency between his ardent pursuit of profit and the supposed higher ethics of socialism. Anyway, his long association in classified military research makes it unlikely he embraced socialism too obviously. In regard to obtaining security clearance, he claimed that he had come within, "the hair of my teeth being associated with Red organizations." He did not elaborate, other than to recall that in 1938 when workers at the Maytag appliance factory in Newton, Iowa, went on strike, he sided with labor and went to investigate. That he took off from work was extraordinary in itself and indicates how passionately he regarded the issue. He thought that by doing so he incurred the displeasure of the ISC administration, however.[110]

One former student likened Atanasoff to Don Quixote, "tilting at windmills." Robert Mather graduated in spring 1942 with a B.S. degree in physics. For the year before that, he did wiring on the

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[107] Philip J. Hart, Provo, Utah, tape-recorded interview made over the telephone with Paul Mobley, 3 December 1997; Atanasoff, interview with Turner, 25 October 1986, 30.

[108] Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone, Paul Mobley, 6 July 1998.

[109] There was a case in particular where the dauntless Atanasoff went to the rescue of two young Mormon missionaries who had gotten in over their heads proselytizing before a hostile crowd at Speakers' Corner in Hyde Park in London. Philip J. Hart, "The Electronic Digital Computer: The Invention and the Inventor," unpublished manuscript, Provo, Utah, 1994, 17 and 19.

[110] For more on the acrimonious Maytag strike, see Shelton Stromquist, *Solidarity and Survival: An Oral History of Iowa Labor in the Twentieth Century* (Iowa City, Iowa: University of Iowa Press, 1993), 108-110 and 162-163; also, Atanasoff, interview with Kaplan, 28 August 1972, 17-25; Atanasoff, interview with Turner, 25 October 1986, 30; Atanasoff, "Advent of Electronic Digital Computing," 260; John V. Atanasoff, transcripts of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 11 July 1968, 46, and 25 July 1968, 29. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 3 and box 33, folder 2).

ABC under Berry's direction. He then served at the NOL with Atanasoff, although not directly under him. There were a number of ISC students at the NOL, and Mather recalled that Atanasoff tried to keep them together, presumably to make it easier to resume their research at ISC after what he hoped would be a short war. For their part, the students enjoyed sharing "JV (Atanasoff) stories" when together socially. By comparing him to the foolish, if noble, ersatz Spanish knight, Mather did not so much mean Atanasoff was impractical, although he did find him a bit "unrealistic" at times. Rather, Mather meant that Atanasoff had a stubborn independence that led him in unorthodox directions, paying little heed to established procedures or what others thought.[111]

Atanasoff admitted his problems with Weaver on Project X, the secret NDRC project that he did for him at ISC, stemmed from obliviousness on his part to Weaver's sensibilities.[112] Still intensely angry thirty years later testifying in *Honeywell v. Sperry Rand*, Weaver considered Atanasoff as "rather bright but queer and opinionated," a "wild guy who would get enthusiastic ideas."[113]

People at the NOL agreed. Atanasoff had little exposure to acoustics before assignment as Chief of the Acoustic Section, Test Division. Unconcerned, he made hasty study and forged ahead confidently.[114] Worse, he set a research agenda at odds with that preferred by the old hands, most with experience in magnetic mines. An observer recalled the consequences: Atanasoff "was attacked, probably viciously, as a driving individual with 'screw ball' ideas. He regarded his acoustic testing assignment as requiring a much different approach than had been possible for the magnetic mines and was unwilling to accept the suggestions of his strongly 'magnetic' colleagues."[115] One offended scientist characterized Atanasoff as, "articulate, aggressive, immodest, opinionated, and unwilling to see any error in any of his ways." Moreover, Atanasoff "was also inclined to try to

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[111] Mather's favorite JV story was about the time fire broke out in a building near the Physics Building at ISC. Atanasoff hurried over to supervise fire-fighting activities, but the firemen chased him away. Robert Mather, Oakland, California, tape-recorded interviews made over the telephone with Paul Mobley, 2, 4, and 9 March 1998.

[112] *Honeywell*, "Transcript of Proceedings," 2,738-2,739.

[113] *Honeywell v. Sperry Rand*, "Summary of Testimony of Dr. Warren Weaver," 6 March 1972, 5-6. ISU, Parks, "Henry L. Hanson Papers" (box 5, folder 2).

[114] Atanasoff, "Advent of Electronic Digital Computing," 256.

[115] William R. Turner, "John Vincent Atanasoff: A Reminiscence of His Early Years at the Naval Ordnance Laboratory," unpublished manuscript, Silver Springs, Maryland, 23 July 1987, 2. ISU, Parks, "John Vincent Atanasoff Papers" (box 20, folder 5).

carry his point by shouting." Not impressed with Atanasoff's new ideas gleaned from books, the scientist scolded sarcastically that: "he could learn a lot about underwater acoustics by just sticking his head under water and holding his breath."[116] Atanasoff prevailed and his program became quite successful and important to the war effort, even if acoustic mines lacked the glamour of atomic weapons or radar.[117]

Atanasoff's supervisors felt fortunate to have him but probably not without mixed emotions. Ralph Bennett, Technical Director for the NOL, remembered Atanasoff as "one of our best idea men," but one who had trouble following procedures. According to Bennett, his "freewheeling" often got him in trouble with the commanding admiral.[118] Even so, in 1945, the Navy presented Atanasoff with its highest award to civilians, the Distinguished Service Award, for among other things, inventing a pressure sweep to destroy a type of underwater mine deployed by the Germans and thought invulnerable to sweeping.[119] The award, without exaggeration, cited him for, "outstanding theoretical knowledge . . . unusual imagination and exceptional mechanical ingenuity, his enthusiasm and indefatigable energy and zeal."[120]

The Navy brass appreciated Atanasoff's ability to accomplish tough assignments and promoted him to Chief, Acoustics Division.[121] His attendance at Project Crossroads exemplified the regard in which the Navy held him. Atanasoff had not planned to witness the atomic bomb blasts since he had a crew to handle onsite details and a surfeit of activities at home base, including the NOL computer project.[122] His commander ordered otherwise because of the primary importance of the tests to the Navy. While admitting that Atanasoff's continued presence in Washington was

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[116] Eric A. Weiss, comments in Saul Rosen, "The Origins of Modern Computing," *Computing Reviews* 31, no. 9 (September 1990), 475-476.

[117] John Vincent Atanasoff, New Market, Maryland, interview with B. Kaplan, 16 August 1972, 12-13. Smithsonian.

[118] George L. Hamlin, "NSWC's J. V. Atanasoff: Recognition Comes Slowly to Computer's Inventor," *On the Surface* 7, no. 36 (14 September 1984), 7.

[119] Early in the war, the U.S. invented the pressure mine, essentially a very low frequency acoustic mine. The Allies decided not to deploy it, since no countermeasure existed and they had more to lose than the Germans if they also developed it. When the Germans began using pressure mines late in the war, it put the Allies in a desperate position. On short order, Atanasoff invented a device to destroy them harmlessly. Atanasoff, "Advent of Electronic Digital Computing," 230; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 731-732; Atanasoff, interview with Kaplan, 16 August 1972, 6-7 and 15-19.

[120] Quoted in John V. Atanasoff (attributed), "Biographical Sketch: Dr. John V. Atanasoff," circa 1950, 8. ISU, Parks, "John Vincent Atanasoff Papers" (box 4, folder 13).

[121] Atanasoff (attributed), "Biographical Sketch: Dr. John V. Atanasoff," 3.

[122] John V. Atanasoff, copy of letter to Harold V. Gaskill, Dean of Science, Iowa State College, 13 June 1946. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 5).

"highly desirable," the officer decided the NOL had to have a man at the Bikini Atoll who could ensure that "silly things are not done," and who was not "afraid of God, the Devil, Man, or the Navy."[123] In fact, Atanasoff made a surprisingly good administrator. For example, the NOL was often desperately short of personnel, and Atanasoff turned out to be an outstanding recruiter of technical talent.[124]

If some people resented Atanasoff, many admired him. Robert Stewart worked with him for several months at the NOL in early 1949. Stewart, who went on to earn a Ph.D. in physics and teach at ISC, eventually becoming chairman of its computer science department, counted Atanasoff as a great influence on his life.[125] When Stewart met him, Atanasoff had recently completed a formidable project to measure vibrations resulting from destruction by the British of German fortifications on the Island of Helgoland, off Denmark, by detonating four or five thousand tons of old, unstable munitions. Other organizations had been asked and refused the project because of the impossibly short preparation time. Atanasoff was warned not to attempt it for that reason and because he had limited experience in seismology. Undaunted, he hastily fabricated twenty-two seismographs he invented and positioned them down the length of Europe. Although not officially requested, he also installed a microbarograph at each station. The devices measured low-frequency sonic vibrations and were also invented for the project. The measurements were made successfully, and Atanasoff was awarded a Citation of the Seismological Society of America and an Admiral's Citation.[126]

The urgency had not abated appreciably when Stewart joined the acoustics group, which had to incorporate what had been learned from the Helgoland and various nuclear explosions into a viable means to detect detonation of atomic bombs around the world.[127] The U.S. had specific concerns about the Soviet Union, although it assumed the totalitarian empire remained technologically so far behind that several years would be required before it could bring a nuclear weapon to fruition. Aided by stolen information, the Soviets actually tested their first atomic bomb later in 1949, and the U.S.

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[123] Author unknown, memorandum regarding the participation of J. V. Atanasoff in Project Crossroads, circa June 1946. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 5).
[124] Atanasoff, interview with Turner, 25 October 1986, 60.
[125] Stewart, interview with Mobley, 14 and 18 November 1997.
[126] J. V. Atanasoff, B. L. Snavely, and John Brown, "A New Instrument for Subsonic Frequency Measurements," abstract in *The Journal of the Acoustical Society of America* 20, no. 2 (March 1948), 222; *Honeywell*, "Transcript of Proceedings," 2,281-2,284; Atanasoff, interview with Kaplan, 16 August 1972, 32-39; Atanasoff, "Advent of Electronic Digital Computing," 259-260; Hamlin, "NSWC's J. V. Atanasoff," 7.
[127] Atanasoff, interview with Kaplan, 28 August 1972, 1-6.

discovered it from residual air pollutants. The stunning news led to considerable worsening of Cold War tensions.

Before the U.S.S.R. tested that first bomb, Stewart recalled sitting in daily staff meetings with the acoustics group and listening in awe as Atanasoff presented his thoughts, "one after the other, each more brilliant than the last, and each requiring a reorientation in thinking on the part of the listeners." Trying to follow his thinking, according to Stewart, "was like trying to get a drink out of a fire hose." Stewart had never met anyone like Atanasoff, who for all his drive and intelligence was also accessible and supportive.[128] On the other hand, Mather, more experienced with Atanasoff, recalled that he made uncompromising demands, and anyone falling short was dressed down in no uncertain terms. That happened often enough that he acquired an unflattering nickname, used behind his back, consisting of a phrase based on his name Atanasoff but that meant to get chewed out.[129]

Whatever faults Atanasoff had, however, lack of humanitarianism was not one. For example, he decided illiteracy in the U.S. must be blamed largely on difficulties inherent in written English. As a cure, he created a replacement binary alphabet with thirty-five letters to precisely cover most sounds, or phonemes, in spoken English. Something like bar coding, letters were comprised of dots, easily "read by man or machine."[130] Atanasoff began the new alphabet during the war as an antidote to his involvement in weapons research. He spent thousands of hours on it spanning many years. More than anything, it represented his life's major work. He pitched it to anyone who listened, with no success finding people willing to give it a try. He thought he had at last the perfect test case with the birth of a grandchild, but his son refused, not wanting his daughter to learn an alphabet no one else would know.[131]

Even if unconventional, Atanasoff gained a reputation at ISC for being progressive and intelligent. People often went to him for advice on research problems; so many sought help that it hindered his own work. For instance, his research on the viscosity of eggs came at the request of the agriculture department. If Atanasoff nonetheless believed some colleagues ignored him,[132] he conceded that he got "great inspiration" from others.[133] And though he complained of intellectual

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[128] Stewart, interview with Mobley, 14 and 18 November 1997.
[129] Mather, interviews with Mobley, 2, 4, and 9 March 1998.
[130] John Vincent Atanasoff, memorandum, (unsigned and undated). ISU, Community Relations.
[131] Atanasoff, II, interview with Mobley, 21 July 1998.
[132] Atanasoff, interview with Kaplan, 23 August 1972, 85 and 88-89; Atanasoff, interview with Merzbach, 5 May 1969, 90 (actually unnumbered).
[133] Atanasoff, interview with Kaplan, 17 July 1972, 32.

isolation,[134] he made frequent trips to professional conferences.[135] For example, the University of Michigan had instituted popular annual summer symposia in theoretical physics, and Atanasoff attended regularly.[136] He thus came to know many of the big names in physics, including most of the originators of the Copenhagen interpretation of quantum mechanics.[137]

Of course, there were no conferences on electronic digital computers, a passion for Atanasoff by the late 1930s. If there had been such conferences, Atanasoff would have had to give the lectures. A number of people had interest in calculators and were moving the technology along smartly in the years before World War II (and, in fact, met to discuss their work), but no one had progressed as far as Atanasoff and Berry, at least in the practical attainment of what computers became.

Atanasoff began as an assistant professor in 1930 teaching the same undergraduate courses in mathematics that he had taught as an instructor. He made no secret of his desire for promotion, particularly since his starting salary of $2,700 for the academic year was reduced to $2,305 due to the Depression.[138] He began developing advanced courses to improve his position about a year after returning to ISC. Most of his classes soon were at the graduate level, including thermodynamics, mathematical physics, kinetic theory, and quantum mechanics, and were courses he developed, representing aspects of physics not taught at ISC previously. He received a joint appointment in the Departments of Mathematics and Physics around mid-decade.[139] When a colleague in physics committed suicide, Atanasoff took the office of the deceased as his private office—so spacious it later served as a classroom but which no one else wanted—and arranged all his classes to meet conveniently in the Physics Building. Depression era budget constraints made promotions infrequent, but Atanasoff became an Associate Professor of Mathematics and Physics in 1936.[140] His promotion to full professor came *in absentia* while he was at the NOL in 1942.

Atanasoff was a demanding teacher, famous on campus for his hyperactivity. Charles Durham, ISC engineering graduate, remembered Atanasoff as a "standout," a common sentiment

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[134] As an example, see Atanasoff, interview with Merzbach, 5 May 1969, 14.
[135] Atanasoff, interview with Tropp, 18 February 1972, 3.
[136] Stanley Goldberg, "Goudsmit, Samuel Abraham," *Dictionary of Scientific Biography*, Supplement II, 1990; Kevles, *The Physicists*, 216 and 218.
[137] Atanasoff, interview with Merzbach, 5 May 1969, 57-58 (actually unnumbered).
[138] "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968.
[139] John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 17 April 1972, 1-4. Smithsonian.
[140] Atanasoff, interview with Kaplan, 23 August 1972, 82 and 87.

among better students. Durham was sometimes tardy for his calculus class, an infraction invariably punished with good-natured ribbing. Atanasoff always came dressed in a clean and neatly pressed blue suit but got so "enthusiastic" lecturing at the blackboard that he left heavily dusted with chalk.[141] Not everyone appreciated his teaching style, heavy on participation. He liked to give each student a problem to solve at the blackboard and then walk around offering encouragement. Some people found him impatient, even arrogant, but never students. In an era of formality between professors and students, colleagues and students alike called Atanasoff, "JV." On the other hand, Atanasoff seemed to relish flunking students who earned it.[142]

Graduate students in particular liked Atanasoff and marveled at his mental abilities.[143] Atanasoff claimed they flocked to him because he was the toughest man in the department and devised interesting and topical projects.[144] No doubt the allure of theoretical physics had something to do with his popularity, even if no one could pursue pure research in physics at ISC. Students also appreciated his accessibility. He could often be found in his office late into the evenings, long after other faculty had left, and available to anyone who stopped by. Atanasoff inspired great loyalty from his graduate students, and some felt that he made a family of them.[145] In any case, it was for them that Atanasoff began the ABC.

ISC conferred its first doctorates in both mathematics and physics in 1933. The first doctorate under Atanasoff went to Charles Wells, who graduated in 1935 in applied mathematics. Wells calculated in his dissertation an approximate solution to the Schrödinger equation for the ground state of lithium. He thus selected much the same problem that Atanasoff had for his dissertation. Lithium, with three electrons, one more than helium, posed a greater mathematical challenge in absolute terms. Wells had to his advantage more work by others as precedent. His result differed from the experimentally measured value by .86 percent, slightly better than other researchers had obtained.[146]

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[141] Charles W. Durham, Omaha, Nebraska, tape-recorded telephone interview with Paul Mobley, 20 March 1998.
[142] Gather, interview with Mobley, 1 July 1998.
[143] Hart, interview with Mobley, 3 December 1997; Mather, interviews with Mobley, 2, 4, and 9 March 1998.
[144] Atanasoff, interview with Kaplan, 17 July 1972, 38.
[145] Mather, interviews with Mobley, 2, 4, and 9 March 1998; Thorne, interview with Mobley, 31 March 1998.
[146] Charles P. Wells, "Calculation of the Ionization Potential of Lithium," unpublished dissertation, Iowa State College, Ames, Iowa, 1935, 5-6 and 29-30; Atanasoff, interview with Tropp, 17 April 1972, 5-7; Charles P. Wells, "Ground State of the LI Atom," *Iowa State College Journal of Science* 12, no. 1 (October 1937), 37.

The next year, Robert G. Wilson became the first of three students to complete dissertations under Atanasoff with topics on the piezoelectric oscillations of quartz plates. Piezoelectric refers to a phenomenon inherent within certain crystalline materials to become electrically charged when placed under stress. The amount of charge is proportional to the degree of deformation, or strain. Piezoelectric crystals also exhibit the converse effect: they become strained when subjected to an electric field. Piezoelectricity was little more than a curiosity until World War I, when French scientists discovered that quartz plates could be excited electrically and made to vibrate and emit high-frequency sound waves underwater. When they produced quartz transducers that could convert the pressure waves that echoed back into electrical signals, sonar was born. Incidentally, the primary motivation for invention of sonar was detection of icebergs, not enemy submarines, as might be supposed. Other uses for piezoelectric crystals were in electrical circuits as filters and oscillators, notably for radio transmitters.[147]

Wilson developed differential equations that rigorously described the vibrations of anisotropic quartz plates and solved them using approximation techniques.[148] Isotropic materials are those with the same physical characteristics regardless along which axis measurements are taken. By contrast, anisotropic crystals have asymmetrical properties along different axes and are the only ones that exhibit piezoelectric effects.[149] Because of the complexity of mathematical analysis, equations of motion for even isotropic oscillating plates had not until then been rigorously defined and solved. Equations of vibration for quartz before Wilson were instead empirical and special purpose.[150]

Philip Hart continued in much the same vein as Wilson. Using experimental measurements from plates he painstakingly cut to exacting specifications from a quartz crystal, Hart worked out the mathematical relationships between the six elastic constants and the higher harmonic frequencies for piezoelectric vibration at constant temperature.[151] He confirmed his original results in postdoctoral research with plates shaped from a second quartz crystal and then investigated how the elastic

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[147] Walter Guyton Cady, *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946), 4-6; Bryan H. Bunch and Alexander Hellemans, *The Timetables of Technology: A Chronology of the Most Important People and Events in the History of Technology* (New York City: Simon & Schuster, 1993).
[148] Robert G. Wilson, "A Study of the Piezo-Electric Oscillations of Quartz Plates," unpublished dissertation, Iowa State College, Ames, Iowa, 1936, 4-5.
[149] Cady, *Piezoelectricity*, 5.
[150] Wilson, "A Study of the Piezo-Electric Oscillations of Quartz Plates," 4-5 and 40.
[151] Philip James Hart, "The Determination of Elastic Constants by Piezo-Electric Methods," unpublished dissertation, Iowa State College, Ames, Iowa, 1939, 4-5 and 71-72.

constants changed with temperature variations ranging from 20 to 70°C.[152] Hart and Atanasoff published the results in *The Physical Review*.[153]

Research through that of Hart on the piezoelectric properties of quartz had been confined mostly to alpha quartz, or low quartz. Alpha quartz is the usual form of quartz found at temperatures below 573°C. At temperatures between 573 and 870°C, alpha-quartz becomes beta quartz, or high quartz, by metamorphosing from a trigonal crystal structure into a hexagonal one.[154] Erwin Kammer extended the work of Wilson and Hart into beta quartz, confirmed that it too is piezoelectric, and calculated its five elastic constants and other values.[155] Kammer finished his dissertation in 1942, the last one under Atanasoff at ISC.

Wilson, Hart, and Kammer had dissertations officially in applied physics. Their work had obvious applications, such as in radio broadcasting and accurate timekeeping mechanisms,[156] but it might well have been termed theoretical. The other four dissertations completed under Atanasoff at ISC were officially in applied mathematics. All seven dissertations had a fundamental commonality, however: They investigated approximate solutions to partial differential equations.[157] The difficulties Wells encountered in calculating the ground state of lithium brought back "full force" to Atanasoff the problem that he had experienced with his own dissertation.[158] Wilson's mathematical model for the oscillations of quartz plates likewise involved partial differential equations solvable only by exceptional effort with approximation methods. The dissertations that followed those of Wells and Wilson also centered upon finding approximate solutions to differential equations. Recognizing that the progress of his students and of science generally was being seriously impeded by the limitations of applied mathematics, Atanasoff made a quest of discovering a better solution method.[159] He

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152 Hart, interview with Mobley, 3 December 1997.

153 John V. Atanasoff and Philip J. Hart, "Dynamical Determination of the Elastic Constants and Their Temperature Coefficients for Quartz," *The Physical Review* 52, 2nd. Series (1 January 1941).

154 Cady, *Piezoelectricity*, 24-25.

155 Erwin W. Kammer, "A Determination of the Elastic Constants of Beta Quartz," unpublished dissertation, Iowa State College, Ames, Iowa, 1942, 1-3 and 47; John V. Atanasoff and Erwin Kammer, "A Determination of the C_{44} Elastic Constant for Beta-Quartz," *The Physical Review* 59, 2nd. Series (1 January 1941); Atanasoff, interview with Tropp, 17 April 1972, 9-12.

156 J. W. Horton and W. A. Marrison invented the crystal clock around 1928, but based on the work of Walter Guyton Cady, a friend and colleague of Atanasoff. Editors of *Electronics, An Age of Innovation: The World of Electronics 1930-2000* (New York: McGraw-Hill, 1981), 36.

157 Atanasoff, interview with Tropp, 17 April 1972, 9 and 13.

158 Atanasoff, interview with Merzbach, 5 May 1969, 70 (actually unnumbered).

159 John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 24 April 1972, 24. Smithsonian.

embarked specifically on a research program to devise with his students a better approximation method for solving differential equations through functional analysis.

A functional is not the same thing in mathematics as the familiar function, although the two concepts are related. A function provides a rule for how numbers from one set, the domain, are to be paired with a second set of numbers, the range. Mathematicians use the word mapping to describe the matching of numbers from the domain with those in the range as defined by the function. Key to the concept of function is that any point in the domain corresponds to only one point in the range.[160]

Somewhat similarly, a functional describes an operation in which a family of functions is mapped into a set of numbers so that each function corresponds to a unique number.[161] That is, the domain for a functional is a family of functions and the assigned unique numbers constitute the range.[162] The concept of functionals originated in 1887 with Italian mathematician Vito Volterra. Atanasoff fell more directly under the influence of Stefen Banach, a Polish mathematician regarded as the founder of modern functional analysis. His *Theory of Linear Operations* (1932, in French) was particularly important.

Among the applications for functionals is that of a polynomial used to approximate another function.[163] For any continuous function or derivative a polynomial exists that approximates it to any desired degree of accuracy.[164] Polynomials have the advantage over many other functions that they are simple to manipulate, although different polynomials are used in practice to describe in piecewise fashion different subintervals of the function being modeled. A complex function can thus be approximated by a family of carefully chosen polynomials, whose functional is usually linear and relatively easy to evaluate. The functional could be used to analyze the amount of error introduced by the piecewise polynomial approximation, for instance.[165]

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[160] R. Creighton Buck, *Advanced Calculus*, 3rd. ed. (New York: McGraw-Hill, 1978), 19-23.
[161] Anthony Ralston and Philip Rabinowitz, *A First Course in Numerical Analysis*, 2nd. ed. (New York: McGraw-Hill, 1978), 42.
[162] Atanasoff, "Advent of Electronic Digital Computing," 233.
[163] Morris Kline, *Mathematical Thought from Ancient to Modern Times* (New York: Oxford University Press, 1972), 1077, 1088, and 1094-1095; Atanasoff, interview with Merzbach, 5 May 1969, 71-72 (actually unnumbered); and *Honeywell*, "Deposition of Dr. John V. Atanasoff," 140-141.
[164] The theorem is attributed to the prolific nineteenth-century mathematician Karl W. T. Weierstrass.
[165] Ralston and Rabinowitz, *A First Course in Numerical Analysis*, 33, 34-35, and 42. As it happens, piecewise polynomial approximations are the broadest category of functions that a digital computer can evaluate.

Atanasoff and his students designed their functional method as a general replacement for approximation procedures then commonly in use, including the Ritz, Treffiz, Boussinesq (or least squares), and Schrödinger perturbation theory methods. Their technique was intended for both differential and integral equations under linear conditions. Instead of substituting a family of polynomials *per se* for the original equation, their method involved selecting a finite number of terms from an expansion function. This was often a Taylor series.[166] A Taylor series is based on a polynomial in the form of a power series, that is, an infinite summation in which terms containing identical differences are taken to incrementally higher exponential powers. A Taylor series can sometimes precisely and conveniently represent another function. In more cases, the original function can be approximated with a finite version called Taylor's formula with a remainder. Whether they used a Taylor, Frobenius, or other power series,[167] Atanasoff and his students defined a functional for the terms of the expansion function in such a way that the problem resolved into finding a solution to a set of linear equations. The resulting number of equations and the overall accuracy of the answer depended upon various factors, particularly the number of terms included from the approximating expansion function.[168]

Summarizing the functional approximation method, Atanasoff and his students conceived of a differential or integral equation as an infinite number of algebraic equations, from which they selected a subset to represent the original equation. By careful attention to conditions of the transformation, a close approximation could be made of the true solution, which could be verified by applying certain tests. Their functional method covered the great portion of important applications, even if limited to linear problems.[169] When the resulting linear equation sets were small, they could be solved by standard methods, such as the common Cramer's Rule. However, equation sets typically became large and difficult to solve as the approximate solution approached the true solution.

The first related work under Atanasoff came from Wells, who explored a technique known as the separation of variables in a 1932 Master's thesis. The method involved reducing a partial

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166 Charles J. Thorne, "The Approximate Solution of Linear Differential Equations by the Use of Functionals," unpublished dissertation, Iowa State College, Ames, Iowa, 1941, 3-8.

167 Charles J. Thorne, "Functional Approximation Methods for the Solution of Linear Differential Equations as Applied to Thin Plates," unpublished Master's thesis, Iowa State College, Ames, Iowa, 1938, 3-5; Charles E. Roberts, Jr., *Ordinary Differential Equations: A Computational Approach* (Englewood Cliffs, New Jersey: Prentice-Hall, 1979), 105-111 and 248.

168 Thorne, "The Approximate Solution of Linear Differential Equations by the Use of Functionals," 3-8.

169 Atanasoff, interview with Tropp, 17 April 1972, 14-24; Atanasoff, interview with Tropp, 24 April 1972, 1-5; John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 11 May 1972, 130-132. Smithsonian.

differential equation to a system of ordinary differential equations for further, presumably easier, solution.[170] Several years later, based on Atanasoff's concept of a functional approximation method,[171] George Lloyd Gross outlined an initial formulation in a Master's thesis entitled "Approximate Solution of Linear Differential Equations" (1937).[172] The next year, Charles J. Thorne applied the method to a problem of elastic plates. The result was also a Master's thesis: "Functional Approximation Methods for the Solution of Linear Differential Equations as Applied to Thin Plates." Thorne anticipated the ABC in his thesis, pointing out that better "machine methods for solving a large number of linear equations" would give use of functionals wider applicability.[173] The previous summer, Atanasoff had written to him, noting that he had "put in considerable time this summer to develop the theoretical aspects," and wanting to know how Thorne, in Utah, was coming with calculations. According to Atanasoff, "what we need, more than anything else, in developing our methods is some practical experience with it."[174]

In, "Use of Functionals in Obtaining Approximate Solutions of Linear Operational Equations" (1939), a dissertation for a doctorate, Gross continued development of the functional method.[175] So did, "Errors in the Approximation of Functions by the Use of Functionals" (1940) by Roy Herbert Cook. His dissertation provided guidelines on how functionals could best be selected to represent a function.[176] Finally, in "The Approximate Solution of Linear Differential Equations by the Use of Functionals" (1941), the culminating dissertation on the topic, Thorne again applied the functional method to plate theory.[177]

Construction of the ABC had progressed a long way by the time Thorne finished his dissertation. He remembered it as the Linear Equations Machine. He had hoped that the electronic computer would be ready for use with his problem, but Atanasoff warned him not to delay work

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[170] Charles P. Wells, "On the Possibility of Solution of Partial Differential Equations by the Separation of Variables," unpublished Master's thesis, Iowa State College, Ames, Iowa, 1932, 5.
[171] Atanasoff, "Advent of Electronic Digital Computing," 232-234.
[172] George Lloyd Gross, "Approximate Solution of Linear Differential Equations," unpublished Master's thesis, Iowa State College, Ames, Iowa, 1937.
[173] Thorne, "Functional Approximation Methods for the Solution of Linear Differential Equations as Applied to Thin Plates," 27.
[174] J. V. Atanasoff, letter to Charles J. Thorne, 16 August 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 18).
[175] George Lloyd Gross, "Use of Functionals in Obtaining Approximate Solutions of Linear Operational Equations," unpublished dissertation, Iowa State College, Ames, Iowa, 1939.
[176] Roy Herbert Cook, "Errors in the Approximation of Functions by the Use of Functionals," unpublished dissertation, Iowa State College, Ames, Iowa, 1940, 19.
[177] Thorne, "The Approximate Solution of Linear Differential Equations by the Use of Functionals."

waiting.[178] Thorne eventually transformed his initial partial differential equation to an algebraic equation set including thirty-one unknowns, far too large for hand solution or computing methods of the day. Even the ABC could not quite have handled that large of equation set. The desired answer remained beyond his reach, but Thorne did get satisfactory results to a lower degree of accuracy.[179]

The situation of Atanasoff and his students was hardly unique. The growing complexity of engineering and science demanded corresponding mathematical tools of greater sophistication, but mathematicians neglected applications before World War II. Instead of addressing topics thought most important, therefore, engineers and scientists tended to pose problems in more elementary terms to allow solutions with available methods.[180] To attack many topical problems forthright, Atanasoff recognized that a combination of more advanced approximation methods and computational devices was the "only way out."[181]

Mathematical approximation is broadly defined as the solution of mathematical problems by methods that do not yield exact answers and is generally used in cases where precise answers are more difficult or impossible to find. It is a complex field of study in its own right but might mean something as simple as discarding less significant parts of an equation in order to solve analytically what remains.[182] Numerical analysis is an area of mathematical approximation based entirely upon arithmetic.

Various numerical methods have been known since before Newton, who added many innovations, most notably the invention of the calculus. Classical numerical techniques depended heavily on the method of finite differences, which involves only additions or subtractions once a problem is set up.[183] The method of finite differences is inherent in the concept of differentiation, in fact, although more specifically, Newton conceived of differentiation in terms of infinite series.[184] Numerical analysis underwent rigorous development in the nineteenth century but necessarily was

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178 Charles J. Thorne, Camarillo, California, tape-recorded interview made over the telephone with Paul Mobley, 26 March 1998.
179 Thorne, "The Approximate Solution of Linear Differential Equations by the Use of Functionals," 14 and 55-56; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 135-145.
180 Atanasoff, interview with Tropp, 17 April 1972, 17.
181 Atanasoff, interview with Merzbach, 5 May 1969, 75-76 (actually unnumbered).
182 Thorne, "The Approximate Solution of Linear Differential Equations by the Use of Functionals," 4.
183 Ralston and Rabinowitz, *A First Course in Numerical Analysis*, 57-62.
184 Kline, *Mathematical Thought from Ancient to Modern Times*, 359-363.

confined to relatively minor problems.[185] The common application was interpolation. Before computers, engineers, mathematicians, and scientists depended heavily on tables of values. Creating such a table began with the laborious calculation of a relatively few pivotal values from fundamental formulae. Simpler numerical techniques were then used to tabulate intermediate values by interpolating between the pivotal values. Moreover, since no table could include all values, the end user often had to interpolate to get specific values.[186] Note that interpolation usually gave only estimates of the true answers.

Numerical analysis in more advanced applications consists mainly of huge numbers of repetitive calculations, which became practical to any extent with the perfecting of electronic digital computers with large memories. Digital computers do only arithmetic operations directly, but by doing them quickly and storing partial results for further use, can be made to contrive solutions to problems in higher mathematics through numerical methods. Conversely, since calculus by definition involves infinite processes, but a digital computer is a discrete device, most computerized solutions to problems in mathematics can only be approximated.

Atanasoff was thus on the cutting edge of not just computers, but what became an important area of mathematics. As an example of the lengths to which Atanasoff went in pursuit of better approximation methods, he arranged for one of his graduate classes to study Nikolay Mitrofanovich Krylov, a specialist in approximation techniques. The readings were in Russian, so Atanasoff found a translator to sit in class.[187] Furthermore, he had translations made of works on approximation theory by Krylov and another mathematician, Mykhailo Pilipovich Krawtchouk.[188] Atanasoff tried to correspond directly with Krawtchouk, but unfortunately, at that time in the midst of the Stalin purges, he was accused of being a Polish spy, arrested, and sent to a labor camp in Siberia, where he died several years later.[189]

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[185] William Aspray, *John von Neumann and the Origins of Modern Computing* (Cambridge, Massachusetts: MIT Press, 1990), 95.
[186] Ralston and Rabinowitz, *A First Course in Numerical Analysis*, 52; for a more complete historical treatment, see Herman H. Goldstine, *A History of Numerical Analysis from the 16th through the 19th Century* (New York: Springer-Verlag, 1977), 68-75 and 145-148.
[187] Thorne, interview with Mobley, 2 April 1998.
[188] Copies of Atanasoff's translations of works by the two mathematicians can be found in the Parks Library at ISU in the archive, "John Vincent Atanasoff Papers" (boxes 5 and 7).
[189] John V. Atanasoff, copy of letter to M. P. Kravcuk (alternate spelling), Kievsky Promyslovyi Institut, Kiev, U.S.S.R, 9 September 1937; John V. Atanasoff, letter to Ukranian (sic) Assoc. for Cultural Relations with Foreign Countries, Kiev, U.S.S.R, 16 November 1937. ISU, Parks. "John Vincent Atanasoff Papers" (box 14, folder 1).

War diverted Atanasoff from the related fields of computers and mathematical approximation, including numerical analysis. Early modern computers and numerical analysis advanced concurrently. The initial success of electronic computers was as much about development of numerical methods as about hardware. One pioneer admonished his eager postwar students: "Design of the machine for the mathematics and design of mathematics for the machine cannot be separated, as they will have their mutual effects on one another."[190] As it happened, others besides Atanasoff, particularly the protean von Neumann, adapted numerical analysis for computers.

The small internal memories of the first computers complicated the task. Goldstine noted that traditional economies of computation reversed with electronic digital computers. Where data storage in the form of hand notes on paper or holes in punched cards had been cheap and multiplication expensive, data storage now became expensive and multiplication cheap.[191] Thus, numerical methods had to be revised consistent with the new economy. In the meantime, and until large, fast memories became available, digital computers had smaller capabilities than commonly understood. Indeed, based on the example of the ENIAC, some authorities thought best use of computers might be to generate tables of values of elementary functions for approximate solutions done manually.[192] That was another reason why the computer pioneers saw need for only a handful of the machines.

Atanasoff found the functional method superior to other methods for transforming differential equations into linear algebraic ones, but like the ABC, even if well developed, it remained a work in progress when he left for the NOL.[193] The functional method might have found wide use, but general-purpose computers programmed with numerical algorithms eventually came to solve differential equations more conveniently. To repeat: the functional method did not produce final answers, but rather, sets of algebraic equations that required further manipulation. As a practical matter, this second part of the solution meant use of a computer programmed with a numerical method

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[190] D. R. Hartree, "Some General Considerations in the Solution of Problems in Applied Mathematics," 9 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 53.
[191] Goldstine, *The Computer from Pascal to von Neumann*, 293-294.
[192] George Stibitz, "Introduction to the Course on Electronic Digital Computers," 8 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 12 and 15-16.
[193] Atanasoff, interview with Halladay, et al., 25 July 1968, 36.

specifically for solving sets of linear algebraic equations. That was the purpose of the ABC, of course. It was also a major purpose for the IAS computer.

Fully computerized numerical solutions are faster but not necessarily better. William Kahan, an authority in computer error analysis, tellingly rewrote Gresham's Law ("bad money drives out good") for computers: "the fast drives out the slow even if the fast is wrong."[194] No matter how done, numerical solutions give only approximate answers in most applications. The inaccuracy that results because the numerical formula cannot yield precise answers is called method error.

Worse, there are other sources of error inherent in computer-generated solutions. Foremost among these is rounding error. Digital computers are restricted by word size, that is, the number of digits available to represent a number. This limitation precludes preciseness in most calculations. Numbers typically must either be truncated or rounded up or down to fit the available spaces in a word. Because of the tremendous number of arithmetic operations a digital computer must complete in the solution of a typical mathematical problem, such errors can accumulate to seriously compromise the accuracy of the final answer.[195] The ENIAC needed to complete about 750 multiplications in a ballistics problem. The IAS computer might have performed 250,000 multiplications for a reasonably good answer to a more complex problem expected of it.[196] Furthermore, rounding is a problem whether a computer uses fixed or scientific notation.[197]

Von Neumann was initially pessimistic about the usefulness of digital computers because of rounding error.[198] In this opinion he took his lead from Harold Hotelling,[199] a statistician who, in 1943, warned about "the neglected question of limits of error." Hotelling had in mind machine methods then available and anticipating when solution of linear equation sets by standard elimination

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[194] William Kahan quoted in David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware / Software Interface* (San Francisco: Morgan Kaufmann, 1994), 249.
[195] Ralston and Rabinowitz, *A First Course in Numerical Analysis*, 2-4.
[196] Herman H. Goldstine and John von Neumann, "On the Principles of Large Scale Computing Machines," 1946; reprinted in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks (Cambridge, Massachusetts: MIT Press, 1987), 325 and 327-328. Where the ENIAC needed about 750 multiplications to complete a problem in ballistics, Mauchly noted that a human computer using a mechanical calculator could complete the problem in "no more than 100 steps." See, John W. Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," August 1942; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 357-358.
[197] Patterson and Hennessy, *Computer Organization and Design*, 249-256.
[198] Aspray, *John von Neumann and the Origins of Modern Computing*, 95-96.
[199] V. Bargmann, D. Montgomery, and J. von Neumann, "Solution of Linear Systems of High Order," 25 October 1946; reprinted in John von Neumann, *Collected Works*, ed. A. H. Taub (New York: Pergamon Press, 1961), Vol. V, 422 and 430-431.

procedures could be substantially automated. Due to rounding error alone, he estimated that at least seven decimal places of accuracy were needed in calculations to ensure an accuracy of one decimal place in the answer of an equation set with no more than eleven unknowns.[200] Like Atanasoff, von Neumann considered large systems of linear algebraic equations fundamental to numerical analysis. He believed solutions of particularly tough partial differential equations might require sets of 100 linear equations or more to approximate adequately. He therefore explored alternate methods of solving linear equations because of Hotelling's dismal conclusion.[201] This changed after British mathematician Alan Turing expressed skepticism about Hotelling's analysis. With Goldstine and others, von Neumann reconsidered rounding error and found it not nearly as big a problem as Hotelling thought in most situations when precautions were taken.[202]

Hotelling knew of the ABC when he issued his dire warning on rounding error and may have been thinking of it. If so, he did not know enough. As President of the Institute of Mathematical Statistics, Hotelling invited Atanasoff to lecture at a national symposium in 1941 dedicated to new calculating machines.[203] Statisticians had great need for better calculating machines, particularly for solving large sets of linear algebraic equations. Atanasoff turned down the invitation upon advice of his patent attorney.[204] Had he not, Hotelling might have learned that the ABC, which used a variation of the common Gaussian elimination method, allowed adequately for rounding error. Atanasoff gave his computer a word size of fifty binary digits to be assured of answers accurate to at least five decimal digits even with twenty-nine unknowns.[205]

By contrast to purely numerical methods in solution of differential equations, the functional method of Atanasoff and his students demanded considerable effort by a mathematician in its

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[200] Harold Hotelling, "Some New Methods in Matrix Calculations," *Annals of Mathematical Statistics* 14, no. 1 (March 1943), 3 and 7.
[201] V. Bargmann, et al., "Solution of Linear Systems of High Order," 421.
[202] Goldstine, *The Computer from Pascal to von Neumann*, 124 and 287-292.
[203] Harold Hotelling, President, The Institute of Mathematical Statistics, letter to J. V. Atanasoff, 28 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 11, folder 20).
[204] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 284-285; John V. Atanasoff, copy of letter to John Mauchly, 7 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).
[205] Actually, Atanasoff worried that even a fifty binary digit word size might not be large enough, but for a different reason. Because the ABC used fixed-point notation, he was specifically concerned more with number drift than rounding error. During the course of calculations on any fixed-point computer, numbers can get smaller and smaller until they disappear from representation. This is called underflow. Conversely, numbers can also expand until they get too large for representation. This is called overflow. Atanasoff, "Advent of Electronic Digital Computing," 253; Atanasoff, interview with Tropp, 11 May 1972, 168-170; Atanasoff, interview with Kaplan, 10 August 1972, 47-49; Atanasoff, interview with Kaplan, 23 August 1972, 33-34.

application and resulted in linear simultaneous equations that could be difficult or impossible to solve themselves before the ABC. The advantage was that the mathematician could ensure the accuracy of the final answer. Furthermore, the numerical method of the ABC avoided method error. If Atanasoff and Berry had gotten the ABC fully operational, and if progress in computers had then halted even temporarily, the functional method could have filled a critical need. As it was, the only published article depicting the functional method was one by Thorne and Atanasoff on its application to thin plate problems.[206]

In addition, Atanasoff presented a paper on a related topic dealing with generalized Taylor expansions to the American Mathematical Society in Columbia, Missouri, in December 1939. Struck by the simplicity of formulae for remainders in a Taylor expansion compared to other types of expansions, Atanasoff in later work sought to show that all expansions could be equated to generalized Taylor expansions.[207] The *Bulletin of the American Mathematical Society* published an abstract of the 1939 paper.[208]

Atanasoff had every reason to expect computers based on the ABC to be a commercial success even if restricted to scientific applications. He anticipated that the ABC would be useful for the considerable number of problems that can be solved explicitly as linear algebraic equations, as well as for those more numerous problems whose solutions could be approximated with such systems. His major interests lie in the latter, of course. He asserted in 1940 that "approximate methods using large systems of linear algebraic equations constitute the only practical method" of solving many differential and integral equations.[209]

Of course, once Atanasoff and Berry realized the viability of the ABC, they recognized that similar computers could be built for other particular mathematical problems or, with flexible controls, for general-purpose applications. The major difficulties involved expanding the memory and devising suitable numerical methods. As an intermediate step, it occurred to Atanasoff how the ABC

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[206] C. J. Thorne and J. V. Atanasoff, "A Functional Method for the Solution of Thin Plate Problems Applied to a Square, Clamped Plate with a Central Point Load," *Iowa State College Journal of Science* 14, no 4 (July 1940), 333-343.
[207] Atanasoff, interview with Merzbach, 5 May 1969, 73-75 and 77-78 (actually unnumbered); Atanasoff, interview with Tropp, 11 May 1972, 126-129.
[208] J. V. Atanasoff, "Generalized Taylor Expansions" (preliminary report), *American Mathematical Society* 46 (January 1940), 5-6 and 27-28.
[209] John V. Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," August 1940; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 315-316.

could be combined with a special attachment to solve integral equations.[210] He was too occupied to pursue his idea, but it did stimulate Mauchly. With the concept of electronic digital computing crystallized in the ABC, and given the momenta of the age, it was all but inevitable that general-purpose electronic computers followed, if not by Atanasoff and Berry, then by others. War impeded developments.

The ABC resulted from Atanasoff's concern for his students and their requirements to solve differential equations. His knowledge of electronics came about much the same way. Since research in physics at ISC focused on applications, Atanasoff decided early that he needed a good grasp of electronics to design measurement apparatus and instrumentation. In 1930, he therefore began intensive study of electronics, learning on his own from *The Thermionic Vacuum Tube and its Applications*, by H. J. Van der Bijl, and the *Radio Amateur's Handbook*. He put together a couple of radio receivers as exercises before beginning apparatus as aids to his students in their experiments.[211] In particular, research in crystals required complex measuring equipment. For example, for Wilson's work on the resonance frequencies of quartz, Atanasoff and Wilson designed two different measuring devices that included variable-frequency electronic oscillators, tuning circuits, amplifiers, and detectors.[212] They also built an oscilloscope, based on the cathode-ray tube, as an instrument to precisely measure electronic signals.[213] Oscilloscopes became available commercially in the 1930s but were often built by users before about 1940.[214] Thus, Atanasoff had acquired a sophisticated working understanding of electronics well before he began the ABC.

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[210] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 844-847; Atanasoff, interview with Merzbach, 5 May 1969, 81-82.

[211] Atanasoff, interview with Merzbach, 5 May 1969, 60-63 (actually unnumbered); Atanasoff, interview with Kaplan, 23 August 1972, 90-91; Atanasoff, "Advent of Electronic Digital Computing," 232.

[212] Wilson, "A Study of the Piezo-Electric Oscillations of Quartz Plates," 18-21; Atanasoff, interview with Kaplan, 10 August 1972, 53-55.

[213] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 111-116 and 128.

[214] Editors of *Electronics*, *An Age of Innovation*, 35.

CHAPTER 3. COMPUTING BEFORE WORLD WAR II

If ours is the Information Age, nothing symbolizes it like the electronic digital computer. Computers are in fact at the heart of information processing. Sophisticated machines for managing information had everyday usage long before modern computers, however. Invention of computers by Atanasoff and Berry and others began only after the earlier devices proved inadequate in some applications. Nevertheless, the older equipment to a surprising degree provided the basis for attempts to create more powerful information-processing machines, of which computers represented by the ABC, EDVAC, and IAS computer ultimately dominated. As important, the original machines established a pattern of development and commercialization repeated by computers, irrespective of the greater involvement by government in computers. Understanding that history is key to understand how and why computers evolved, and why direct government support was unnecessary.

Among the close ancestors of electronic digital computers can be counted adding machines, calculators, and above all, tabulating equipment. Less obvious but also important were typewriters, cash registers, telegraph equipment, and telephones. Commercial developments of these seminal technologies emerged independently but practically simultaneously in the mid- to late-nineteenth century. All attained essential forms by the twentieth century and were commonplace in factories, stores, and offices by the 1920s. The enterprises that manufactured and sold data-handling machines by then had become identified collectively as the office appliance industry. Facets of office appliances are part of computers still. Furthermore, while the original data-processing machines established a technological foundation for computers, the business practices of the office appliance industry in the late nineteenth and early twentieth centuries evolved into those of the information-processing industry after World War II. Office appliance companies discovered early that they had to maintain close associations with customers and competitive prices, while continually offering productivity-improving enhancements.

No corporation had greater influential on the office appliance industry than National Cash Register. As its name indicates, NCR made cash registers. It held about 95 percent of the market into the 1920s.[1] The link between cash registers and other office appliances and computers may seem tenuous, but at the start of the twentieth century, NCR introduced electrically driven cash registers

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[1] James W. Cortada, *Before the Computer: IBM, NCR, Burroughs, and Remington Rand and the Industry They Created, 1865-1956* (Princeton, New Jersey: Princeton University Press, 1993), 3-4, 63, 65, 87, and 178.

whose outputs combined to give ongoing total sales for a store.[2] The company diversified into adding machines, calculators, accounting machines, and finally, computers.[3] NCR was awarded two of the three earliest patents in the United States for electronic computing circuits in 1940. IBM won the other patent that year and two more the following year.[4]

More important, NCR pioneered management practices that came to characterize the industry, particularly at IBM. Thomas J. Watson got fired from NCR before taking charge in 1914 of the company that became IBM. A casualty of office politics at NCR, the legendary Watson admitted frankly that he had learned core policies from his former employer that he implemented at IBM.[5] Those policies played as key a role in making IBM the largest manufacturer of computers as they had at NCR helping it become the foremost producer of cash registers. Furthermore, when NCR lost primacy in cash registers beginning in 1987, it was to IBM.[6]

The success of NCR was principally due to one man: John Patterson, regarded as the "grand-daddy of all corporate innovation champions."[7] Patterson did not invent the cash register or found NCR. He bought controlling interest in the nascent firm in 1884 and then ran it brilliantly. As a fundamental innovation, he vertically integrated his corporation before the adoption of that organizational structure at other office appliance companies. Activities from engineering, to manufacturing, to sales were centrally and closely managed at NCR.

Patterson is most famous for recognizing salesmen as the crucial link with customers. Patterson became head of the National Manufacturing Company (the name was changed to National Cash Register in 1894) as cash registers were being introduced to the world. Reluctant customers had to be persuaded of their benefits and taught their operation, because they were not obvious at first. A storeowner typically kept cash in a cigar box or a special drawer mounted under the checkout counter, making it easy to pilfer money. It fell to NCR's salesmen to convince storeowners that stealing by

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[2] Emerson W. Pugh, *Building IBM: Shaping an Industry and its Technology* (Cambridge, Massachusetts: MIT Press, 1995), 110. Charles F. Kettering invented the electrically driven cash register. He then left NCR and invented the electric starter for automobiles based on the same concept as a cash-register drawer opener he had perfected using a high-torque electric motor. He later became Director of Research for General Motors.

[3] Cortada, *Before the Computer*, 5 and 178.

[4] RCA was awarded the next two patents on electronic computing circuits in 1942. However, RCA's patents were associated with control of antiaircraft guns. Pugh, *Building IBM*, 325. See, "Appendix C: Early Electronic Computing Circuit Patents."

[5] Pugh, *Building IBM*, 29-31.

[6] Cortada, *Before the Computer*, 177.

[7] "A Survey of Innovation in Industry," *The Economist* 350, no. 8107 (20 February 1999), 15.

employees warranted purchases of cash registers. Clerks opposed the new machines unsurprisingly. Adding to their disadvantage, the salesmen had an unsavory reputation themselves.

Patterson understood that a vendor of machines for safeguarding cash needed to convey an image of integrity. Accordingly, he elevated the status of salesmen within the company and instilled in them a sense of professionalism. He implemented a dress code and rules of conduct, had salesmen memorize low-pressure and standardized sales pitches at a company Marketing School, and sent them out burdened with tough sales quotas. In return, he guaranteed exclusive sales territories and provided extensive and creative corporate-wide advertising support. NCR salesmen delivered sales in spades, and the company's cash registers soon became ubiquitous around the globe.

NCR salesmen had another essential task besides selling and teaching, without which NCR could not have been so successful: they kept corporate headquarters abreast of customer dissatisfaction. This was important because another part of Patterson's business plan was product development. He believed engineering as crucial as selling. From the time Patterson took over until World War II, NCR applied for around 2,400 patents. Most innovations originated in response to customer complaints and immediate needs.[8] However, the fact that NCR filed early patent applications on electronic calculating circuits suggests it looked ahead.

NCR set the standard for the practices of the office appliance business, but typewriters better than cash registers illustrate the general pattern of product development. While the typewriter, like the cash register, might seem too humble of antecedent for the computer, historian of computers James Cortada maintained that it played a crucial role in the rise of the office appliances industry, and thence to electronic digital computers. Indeed, the history of the computer has had notable similarities and connections to that of the typewriter.

The typewriter was the initial identifiable technology to emerge into what became the office appliance industry. Its rapid acceptance encouraged manufacturers to diversify. Companies successful at producing typewriters often expanded into other office appliances. The engineering and manufacturing requirements of typewriters and other appliances were similar, and features transferred from typewriters to the other devices: the keyboard being an obvious example. Most important, customers for typewriters often purchased other office machines. Therefore, typewriter vendors became attuned to the idiosyncrasies of the office appliance market as it formed.

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[8] Cortada, *Before the Computer*, 12 and 65-70; Pugh, *Building IBM*, 29-31.

A history of the typewriter might go far back into the eighteenth century. Patents were filed in the United States and Europe on "writing machines" before the mid-nineteenth century. However, the first commercially successful machine is attributed to Christopher Latham Sholes, an American, who began its development in the 1860s. Sholes sought help from financier James Densmore when ready to begin production. Densmore turned to E. Remington and Sons, a weapons manufacturer wanting to diversify. Sales of what became the Remington No. 1 began in 1874. The No. 1 looked something like a sewing machine, because it owed part of its design to that already mass-manufactured domestic appliance. It was not much of a typewriter by later standards and produced capital letters only. Interestingly, the original market was not thought to be businesses, but authors, lawyers, and clergymen. Moreover, although the typewriter is strongly identified with female secretaries, women were not at first considered strong enough to use it. It was only after too few men could be found to operate typewriters, and after improvements allowed less exertion in their use, that women became typists.

The typewriter business grew quickly but not fast enough for Remington. The company preferred manufacturing to marketing, so in 1878 it enlisted another firm, Fairbanks and Company, to do the selling. Meanwhile, other manufacturers entered the business and competition depressed prices. Remington typewriters remained most popular. Even so, the arms maker opted out, unprepared to put the emphasis on marketing needed to continue competing effectively. Densmore severed ties and set up a new company with a similar name—the Remington Standard Typewriter Company—to continue making Remington typewriters. The enterprise suffered ups and downs but thrived overall. It never dominated the typewriter market as NCR did that of cash registers but stayed the largest producer.

A manufacturer of typewriters had to scramble to sustain the steady stream of innovations necessary to ensure its ongoing existence. Around 6,200 patents were issued on the typewriter in its first forty years of commercialization. The basic features of manual typewriters had been conceived by 1900, by which time hundreds of manufactures had sold some 100,000 machines. Standardization of design and quality followed, resulting in typewriters becoming a commodity. That meant customers bought mainly on cost, placing further downward pressure on prices even as manufacturers fought to distinguish their typewriters by bringing out better features. Competition also caused ongoing consolidation of manufacturers. Cortada noted that in 1904 there were some one hundred makers of typewriter in the U.S. The number had shrunk five years later to eighty-nine firms, but astonishingly, most had been created since 1904. American manufacturers of typewriters dwindled to four major ones in the 1930s.

The same trend of consolidations extended to and among other office appliances and their manufacturers, although it became increasingly difficult for new firms to enter the industry as advantages to economies of scale became overwhelming. As an example, four of eight bookkeeping machine vendors in 1924 had typewriters as their primary product. The main product of another three was adding machines. Shared characteristics aided consolidation. All the office machines were high-tech products for their day. Typewriters, no less than calculators or other office appliance, required sophisticated engineering in design and precision machining in manufacture. Moreover, the appliances had similar features. More important, although targeted originally for different customers, the various appliances came to be purchased by the same ones and entailed similar marketing problems. Fundamentally, the office appliance industry strove to sell equipment in volume that dealt more quickly, reliably, and cost effectively with growing quantities of information.

More demanding data-handling requirements coincided with increases in sizes and activities of businesses and government. The U.S. economy grew by leaps and bounds from the Civil War onward, periodic economic downturns notwithstanding. The GNP of the nation went from $9.1 billion per year in the late 1860s to around $67.7 billion annually by 1921. Moreover, the rate of growth of investments in office machines is estimated to have exceeded that in manufacturing by as much as four times in many years.[9]

On a less productive note, much market growth for office appliances came from, or because of, federal government, which expanded markedly, particularly beginning with the Great Depression. The relationship between the federal government and office equipment was complex, however. On one hand, government provided a huge market. It became IBM's largest customer by end of the 1930s. On the other, it is doubtful that many ambitious government programs could have been implemented without the machines. With the New Deal, for example, the newly created Social Security Administration began mailing out millions of checks printed on punched tabulator cards. Moreover, legislation stimulated purchases of office appliances both inside and out of government. An example was federal income taxes, first imposed in 1913, which forced many businesses to upgrade accounting tools. As another example, NCR introduced a bookkeeping machine specifically to handle the records involved when Washington started backing home loans. As yet another influence, standardization of government forms further stimulated vendors to standardize appliances.

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[9] Cortada, *Before the Computer*, 5-8, 10, 13-18, 20-22, 23-24, 59, 79, 83, 91, 101, and 280-281. Some information is from, "Table 1.1 Gross National Product for the United States, 1869-1921 (dollars in billions)," 8.

Finally, antitrust actions by the federal government reined in the expanding information-processing industry and, while it may have furthered competition, in other respects likely had an adverse effect on innovation. NCR, Burroughs, IBM, Remington Rand, American Telephone and Telegraph (AT&T), and Microsoft have all been targets over the years. Fear of the government probably kept IBM from bidding on EMCC, for example. As another example, a 1956 antitrust agreement precluded AT&T from venturing into commercial computers.[10]

As epitomized by the cash register, but more by the typewriter, the pattern of development for an office appliance can be summarized as follows: An inventor brought a prototype to market after a long gestation involving many inventors. The commercializing inventor then lost control of his enterprise to professional managers with better grasp of production and marketing considerations. Other firms entered the market and the originally identified customers became less important as the market broadened. Ensuing competition meant low profit margins, fostering consolidations in attempt to increase sales volumes. Competition also forced ongoing innovation.

Cortada stressed that innovation was not uncontrolled or reactive, but adopted by manufacturers as a deliberate and essential business strategy. An appliance developed rapidly until it reached a standard form. Innovation continued with discovery of unanticipated uses by both vendors and customers. New applications spawned new features and vice versa. However, an innovation gave only short-term advantage until others copied or improved upon it. Manufacturers ordinarily refined a technology incrementally as far as possible before making a radical improvement. Dramatic changes typically raised risks and costs, and vendors could not afford for their products to become expensive relative to others that satisfactorily handled the applications of economy-minded customers.

Finally, an office appliance maker needed to be adept at dealing with customers and could no more slight marketing than product development. Indeed, a connection existed between the two. Most successful innovations derived from interaction with customers, who then had to be coaxed into trying them and taught their use. Moreover, employees of customers typically saw new equipment as a threat, and their resistance had to be overcome. As further need for vendor-customer interaction,

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[10] Tom Watson Jr. quoted in Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York City: BasicBooks, 1996), 118; Pugh, *Building IBM*, 57; Cortada, *Before the Computer*, 74-78, 116-117, 112-113, 145-147, and 242-246; Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988), 120-121.

although increasingly reliable, appliances required servicing by manufacturers' representatives.

The computer has followed about the same pattern of development as an office appliance, although at a faster pace. Consider that Eckert and Mauchly did not invent the computer but were among the first to attempt to take it to market. They proved unable to retain control of their company, losing it to Remington Rand. The computer attained standard form with the von Neumann architecture. Even so, the computer has undergone extensive innovation, including several generations of technologies.[11] The market for computers has expanded from a few entities to include potentially everyone for all kinds of uses. Meanwhile, manufacturers faced intense competition, resulting in considerable turnover. Moreover, the trend of merging technologies has continued, so that the whole of information processing has become dependent on the computer. The computer, like an office appliance, is now (largely) standardized, affordable, and plentiful. All this suggests that digital computers took the technologies of data handling to higher levels but remain fundamentally the same business as office appliances.

If the connection between typewriters and computers seems a stretch, note that two typewriter manufacturers between the world wars became the major vendors of computers afterwards.[12] One was Remington, which became Remington Rand in 1927. The other company, IBM, created the market for electric typewriters in the 1930s.[13] Typewriters remained a larger source of revenue than computers for IBM through the 1950s. The corporations moved into computers somewhat differently, however. Remington Rand began delivering internally developed electronic calculators in 1951 but purchased most of its computer technology by acquiring EMCC and ERA.[14] IBM bought numerous related patents and sponsored research by others;[15] even so, it developed substantial capabilities internally.

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[11] Computer generations refer to commercial computers and their underlying technologies. Commercial computers with vacuum tubes constituted the first generation, those with transistors the second generation, and so on. Some experts say that the latest generation, the fifth, are computers based on microprocessors. David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware / Software Interface* (San Francisco: Morgan Kaufmann, 1994), 38-40.
[12] More generally, of twelve major manufacturers of commercial computers in the U.S. in 1954, seven were office appliance manufacturers. Flamm, *Creating the Computer*, 82. See, "Table 4-1. Chief Producers of Digital Computers, 1954."
[13] Cortada, *Before the Computer*, 5, 18, 63, 88, 96, 150, 155-157, 222, and 273-275.
[14] Saul Rosen, "Electronic Computers: A Historical Survey," *Computing Surveys* 1, no. 1 (March 1969), 12. The earliest Remington Rand electronic calculator was the 409-2. With 1,476 vacuum tubes, the 409-2 probably compared to the IBM 604 Electronic Calculating Punch.
[15] Pugh, *Building IBM*, 77.

Experience with typewriters helped Remington Rand and IBM market computers, but tabulating equipment led most directly to computers. Tabulators, also called accounting machines, were high-speed adding machines designed to manipulate large amounts of data from punched cards. Tabulators and accessories constituted the founding technology for mass data processing and did the job of computers in a less demanding age. Such equipment comprised only a small part of the office appliances business as late as the early 1920s. Its popularity grew proportionally with need to handle more data, so its development was especially vigorous between the world wars. It had become the most significant sector of the office appliance market by World War II. By then, punched-card equipment was identified collectively as EAM[16] equipment to include a variety of related machines.

It was not a coincidence that the first organizations to adopt computers tended to be those most dependant on EAM equipment. The close relationship explains why customers for the UNIVAC demanded that Eckert and Mauchly offer accessory equipment that could import data from punched cards. The data-handling equipment they already operated used such cards, and card-to-tape and tape-to-card converters made the transition to computers easier and less costly. Moreover, when Eckert and Mauchly developed the UNIVAC as a system, as IBM and other manufacturers also did with their computers, they kept with a tradition established with tabulating equipment. An installation of EAM equipment similarly involved a system: a series of machines including, at a minimum, tabulators, keypunches, and sorters. It could include a host of other accessories, but all stored and shared information on punched cards.[17]

IBM and Remington Rand had thc early advantage in computers because they dominated the EAM equipment market worldwide and thus already understood the essence of the technology and market that computers came to fill. Even so, the transition proceeded slowly. IBM had greater sales in EAM equipment than computers until 1962. More telling, Sperry Rand did not break even on computers until the next year, 1963, and did so then only because it introduced the UNIVAC 1004, a machine more related to EAM equipment. The first computers were expensive and difficult to use, and many organizations continued to find EAM equipment satisfactory and a better value.[18]

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[16] EAM stands for electric accounting machine.

[17] W. J. Eckert, *Punched Card Methods in Scientific Computation* (New York: Thomas J. Watson Astronomical Computing Bureau, Columbia University, 1940), 12; Cortada, *Before the Computer*, 44-45, 91, and 131; Pugh, *Building IBM*, 91-92.

[18] Cortada, *Before the Computer*, 266-267; Campbell-Kelly and Aspray, *Computer*, 130 and 135-136.

The inventor of tabulating equipment, and arguably the founder of IBM, was Herman Hollerith. He graduated from the Columbia School of Mines and obtained employment with the U.S. Census of 1880 analyzing data on water and steam power use by the iron and steel industry. Most information for the census was compiled by hand, and another employee suggested that a machine using paper cards could be built to do much of the work. Hollerith agreed. He left in 1882 to become, first, an instructor of mechanical engineering at MIT; next, an assistant examiner for the U.S. Patent Office; and then, a self-employed patent consultant. He thought meanwhile on the problem of the census and submitted his first of many patent applications on tabulating equipment in 1884.

His initial setup involved recording data in paper tape with a pattern of small round holes made with a hand punch. He reverted to the original idea of cards to gain flexibility in handling data.[19] His tabulating machine worked like a press. It consisted of a hard rubber base upon which a punched card to be read was laid against stops to ensure its correct position. Inserted into the base and arranged to coincide with all possible hole locations were small open cups partly filled with mercury. The matching component of the press was the reciprocating box. Spring-loaded retractable pins protruded underneath, spaced exactly to mate with the mercury cups. Each pin was part of a separate electrical circuit that included its corresponding mercury cup and dedicated electromechanical counter.

To tabulate, the operator lowered a handle that brought the box into precisely positioned contact with the base. The card forced the retraction of the pins. At a hole, however, a pin dipped unrestrained through the card and into the mercury, completing its circuit, and incrementing the corresponding counter by one. Thus, a tabulator counted holes at each location in the cards. As simplistic as that may sound, complicated arrangements of data could be analyzed using combinations of circuits.[20]

Hollerith's ingenious concepts were not entirely his own. Storing information by holes in cards went back a long way, most famously to Joseph Marie Jacquard, a Frenchman, who early in the nineteenth century invented the Jacquard loom that automatically wove patterns in cloth following a program of instructions formulated as holes in cards. Furthermore, Hollerith's tabulator resembled an automatic telegraph system invented some years before. Even if his ideas were not exactly new, the application was, and Hollerith won his patents.

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[19] Pugh, *Building IBM*, 1-5.

[20] Herman Hollerith, "An Electric Tabulating System," 1889; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 138-141.

With basic tabulating equipment thus defined, endless improvements began, first by Hollerith, then by others. The sorter was a related invention. The first one consisted of a wooden box divided into compartments. Each tabulating circuit could both activate its counter and open a lid on a corresponding sorter compartment. The operator then picked up the card, placed it into the open compartment, and closed the lid. This procedure allowed sorting of cards by attribute. The table-mounted punch was another invention essential to the success of tabulating equipment. Making holes with a hand punch was simply too fatiguing. Later versions called keypunches incorporated typewriter-like keyboards.

Hollerith borrowed money from a brother-in-law to build his first equipment. Its shakedown trial came in 1886 compiling vital statistics for the Baltimore Department of Health. Other relatively small jobs followed, all completed successfully. The big break for Hollerith came with a huge contract for the U.S. Census of 1890. It involved over ninety of his machines, which the Western Electric Company fabricated, except for punches, built by Pratt and Whitney Company.

Hollerith leased about half of the tabulating equipment for $500 each per year and the rest for $1,000 apiece per year. The equipment allowed the government to analyze more data in more ways and complete the total job faster and more accurately than in the past. It is doubtful the government saved money, however. Costs per capita rose from 11.5 cents for the 1880 census to 18.4 cents for the census of 1890.[21] Thus, the first major use of computing equipment manifested a phenomenon evident even today. It is still questionable that computers save money overall, but they unquestionably permit analysis of data impossible any other way.

The results coming from the 1890 census prompted various foreign governments to place orders. These included Austria, Italy, Norway, and Canada. Russia used Hollerith equipment in its census of 1897 for compiling data on its 129 million citizens.[22]

Meanwhile, Hollerith incorporated as the Tabulating Machine Company in 1896. He also solicited orders from commercial interests, hoping to create a steadier business than intermittent census compiling permitted. He redesigned his equipment to that end. Most significant, he replaced the original simple dial counters with accumulators that added all digits simultaneously. Additionally, he reconfigured the cards and developed an automatic sorter.[23]

The first major order from business came in 1895 from the New York Central Railroad. Contracts with other railroads followed. The Pennsylvania Steel Company was the first industrial

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[21] Pugh, *Building IBM*, xi, 6-14, and 21.
[22] Cortada, *Before the Computer*, 49.
[23] Pugh, *Building IBM*, 15-16.

concern to order. In 1902, Marshall Field, a Chicago department store, became the first retailer. Insurance companies then discovered Hollerith's equipment. Slowly a market for tabulators formed, although the expense of the equipment meant only organizations with large data-handling requirements could justify it. Moreover, accountants and clerks often resisted its installation, seeing potential for job loss on the assumption that a low-skilled operator and tabulator setup could replace several clerks. Whether or not unemployment actually resulted due to office machines is uncertain.[24]

For the census of 1900, the U.S. government again leased Hollerith equipment, including 311 tabulators, 20 sorters, and 1,021 punches. The processing rate of tabulators had improved markedly and advances had been made in the automatic operation and reliability of all equipment. Hollerith was paid $428,239 for his machinery and services, including cards used. He may have only have begun to break even on his development costs,[25] but some regarded the expenses as unjustified. The perception intensified when Hollerith started charging rental based on card use. For every 1,000 cards tabulated and sorted, he demanded 65 cents and 18 cents, respectively. With increases in card-processing rates, total expense of leasing went up significantly. A year's lease could run more than the cost of the machine.[26] Another sore point for users was that Hollerith insisted they purchase cards from him. The policy was at least partly justified to ensure card quality, but at 85 cents to $1.00 per thousand cards, Hollerith made a handsome profit. Customers used many millions of cards.[27]

Adding controversy within the Census Bureau was suspicion that Hollerith had obtained his contracts unfairly. Some believed the worst confirmed when a former director of the Census became head of the British Tabulating Machine Company. The new director removed all the company's machines from the Census Office, and with money specifically appropriated by Congress, ordered development of its own tabulating equipment based on Hollerith's designs. Hollerith could do little against the government. The U.S. Census of 1910 thus used Hollerith-derived equipment without compensating him.[28] However, problems with the new machines forced the reinstallation of the old Hollerith equipment to complete the census.

Nonetheless, Hollerith had lost the business of the Census Bureau. Worse, the agency allowed its employees to apply for patents as their own. James Powers, a prolific inventor for the Census, took advantage of that policy and left in 1911 to establish the Powers Accounting Machine

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[24] Amy Sue Bix, *Inventing Ourselves Out of Jobs?: America's Debate over Technological Unemployment, 1929-1981* (Baltimore: John Hopkins University, 2000), 84-91.
[25] Cortada, *Before the Computer*, 50-53.
[26] Pugh, *Building IBM*, 21.
[27] Cortada, *Before the Computer*, 53-54.
[28] Pugh, *Building IBM*, 21.

Company to compete head-on against Hollerith. Powers initially offered only a keypunch and sorter. In 1914, he added a printing tabulator. The Tabulating Machine Company did not have a printer, which became a major selling item for Powers. Powers eventually developed a full line of EAM equipment with evidently superior but nevertheless intrinsically limited features. Hollerith's patents prevented Powers from incorporating electrical components. Furthermore, Powers equipment proved less reliable.[29] It never gained more than a fraction of the total market for EAM equipment despite the preference given it by the Census. Nor did Remington Rand's purchase of the Powers Accounting Machine Company substantially improve its market share.

In 1911, Hollerith participated in merging his company with the International Time Recording Company and the Computing Scale Company of America to create the Computing-Tabulating-Recording Company (CTR). The name was changed to the International Business Machines Corporation in 1924. Hollerith stayed for a time as autonomous inventor and member of the board. Watson got the job of general manager in 1914. He became president the following year, by which time Hollerith had resigned from the board of directors and exerted little further influence on the company.[30]

Watson concluded that tabulating equipment had greater potential than most other products made by IBM. Over the years he dropped less profitable or strategic lines, such as meat scales, podiums, and microphones, to focus more on punched-card equipment.[31] Furthermore, Watson kept key policies implemented by Hollerith, including his preference for leasing rather than selling equipment. Leasing tended to generate a more stable revenue stream, because customers accepted and retained the expensive tabulating equipment more readily if they could avoid capital expenditures. IBM predominantly leased equipment into the 1970s,[32] long after computers had become its major product. Watson also continued to demand that customers purchase punched cards exclusively from IBM. About three-quarters of revenue for CTR in 1915 came from card sells, so it is not hard to see why.[33]

Most important, Watson, like Hollerith, took keen interest in product development. He had to build an engineering department from scratch with only a small initial budget, however, because

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[29] Cortada, *Before the Computer*, 43, 57-58, and 62-63.
[30] Pugh, *Building IBM*, 26-28, 35, and 39.
[31] Cortada, *Before the Computer*, 150.
[32] Pugh, *Building IBM*, 45. IBM typically offered to either rent or lease its equipment, with rent defined as a short-term lease. Cortada, *Before the Computer*, 152-153.
[33] Cortada, *Before the Computer*, 54 and 58.

Hollerith had contracted out equipment development and manufacturing. As one brilliant decision, Watson hired James W. Bryce, who became chief engineer in 1922. Bryce had studied mechanical engineering at New York City College and was already an accomplished inventor before joining IBM. He accumulated some 500 patents in his lifetime and was honored by the U.S. Patent Office in 1936 as one of the "greatest living inventors." Bryce supervised a number of similarly talented engineers who produced many innovations. Most of their creative efforts went into EAM equipment. Unfortunately, IBM engineers did not publish and have received little recognition from historians.[34] Besides its inventions, IBM aggressively purchased related patents by others. In fact, most of its patents for years originated outside the company.[35]

IBM held the lion's share of the market for tabulating equipment, but its rivalry with Remington Rand was no less intense for that. Other companies also tried to compete. Thus, tabulating equipment had to abide by the same market rules as other office appliances. Lower prices and better features meant more customers, who always demanded improvements but purchased only those offering good value. IBM and Remington Rand had to bring new features out constantly while struggling to keep prices competitive. Both companies went to great expense to completely refurbish their lines of punched-card equipment in the 1920s and again in the 1930s.[36]

Powers bested the Tabulating Machine Company at the start with its popular tabulating printer. CTR developed an equivalent and cheaper printing attachment in 1917, although it did not become generally available until after World War I. Also to its advantage, Powers had a mechanical linkage system that permitted easy change of applications. Changes on a Hollerith tabulator involved laboriously rewiring the machine. IBM took the lead by adding a plugboard with quick-change connections, like a telephone switchboard. IBM then made the plugboards themselves quick-change. Customers could keep inventories of detachable plugboards, each pre-wired for a different application. IBM published a bulletin of useful wiring configurations, many devised by customers.[37]

Other milestones for punched-card equipment included the electric keypunch (1917); typewriter keypunch for punching and typing simultaneously (1928);[38] and tabulators with full alphanumeric printing capabilities (1930s). In 1928, IBM patented an 80-column card for use with rectangular punches. IBM and Remington Rand had used a variety of cards previously, but most

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[34] Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 129.
[35] Pugh, *Building IBM*, 39 and 77-78.
[36] Cortada, *Before the Computer*, 105-106 and 108-110.
[37] Pugh, *Building IBM*, 38, 40, and 63.
[38] Cortada, *Before the Computer*, 56.

common for both were similar 45-column cards for round punches. IBM's new card offered greater data-recording flexibility, strength, and other advantages. Most notably, it prevented mixing of IBM and Powers equipment, and in effect, furthered IBM's market dominance. IBM standardized on the 80-column card as the "IBM card." It proved a big success and remained in common usage into the 1970s for computer systems. As another milestone, IBM in 1931 brought out the first EAM device to perform multiplication. The Type 600 Multiplying Punch took two numbers from a punched card, multiplied them, and punched the answer into the same card. A more sophisticated version was introduced two years later.[39]

On the whole, customers regarded Remington Rand and IBM as having similar products. Nevertheless, Remington Rand never came close to matching IBM's market share in EAM equipment. The federal government estimated that IBM had about a nine-to-one advantage at one point. One reason was that IBM for a time used its patents to prevent Powers from converting its machines to electricity and thus limited its potential. Remington Rand never proved as proficient an innovator, however.

More of the reason IBM enjoyed market advantage, according to Cortada, was it became a focused corporation earlier than Remington Rand, which suffered ongoing internal turmoil as it attempted to absorb acquisitions. Remington Rand as consolidated in 1927 had roots in thirteen companies. It added Powers the same year and continued to acquire companies through 1933. Remington Rand thus offered greater diversity of products than IBM. That also made it more difficult to manage, particularly with the Depression, a challenging time even for well-established companies.[40] Finally, IBM proved better at manufacturing and, especially, marketing.[41] IBM salesmen were legendary for applying skills derived from NCR.

EAM equipment by World War II performed all the operations of arithmetic and was adept at handling large quantities of data; that is, it essentially did what a computer does. Even the most advanced EAM equipment was not a true computer, of course, lacking efficient electronic logic circuits, large memories, and attributes anything like the von Neumann architecture. Still, driven by a commercial market with insatiable demands for better data-handling machines, IBM and other

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[39] Pugh, *Building IBM*, 48-52; Cortada, *Before the Computer*, 106.

[40] Getting its acquisitions to work in harmony continued to be a problem for Remington Rand. After it purchased ERA in 1952, Remington Rand had three separate computer groups: UNIVAC, ERA, and another original to it. It them merged with the Sperry Corporation in 1955. Flamm, *Creating the Computer*, 107.

[41] Cortada, *Before the Computer*, 114-116, 155, and 219.

companies had begun experimenting with electronic computing circuits before World War II. Bryce is alleged to have started considering them in 1915.[42] By the war, his company had developed, and in several cases, patented computing circuits using vacuum tubes.

As one achievement, an engineer for IBM invented an electronic circuit in 1941 that used binary code to represent decimal numbers. The hybrid system handled decimal numbers with about half the vacuum tubes needed in the much bulkier circuits of the ENIAC several years later. Binary-coded decimal circuits became common after the war, particularly for calculators requiring frequent number entries.[43] Eckert and Mauchly switched to binary-coded decimal for the UNIVAC.

Moreover, although serving a conservative and cost-conscious market, IBM expended a great amount of effort and money in computer research even before World War II. Beginning in 1939, it developed the ASCC,[44] more commonly known as the Harvard Mark I. General purpose and programmable, the ASCC was the largest electromechanical digital computer ever built. It weighed about five tons and contained seventy-two accumulators. It has been attributed to Howard Aiken, a graduate student in physics at Harvard at project's start, but who is best described as architect. He laid out the general design but believed electronic circuits unreliable and refused to consider them. IBM did the difficult engineering of the ASCC but quite unjustly has received little credit. The company invested several hundred thousand dollars in the design, construction, and startup of the giant computer. IBM donated it in 1944 to Harvard, and the Navy acquired its use. The ASCC allegedly did calculations for the first atomic bomb, although, like the ENIAC, it served better to compute mathematical tables.[45]

The ASCC initiated a long-term, informal strategy by IBM to extend its capabilities by exploring "supercalculators," either on its own or by funding research by others. World War II interrupted those efforts, although IBM built a couple of fast relay calculators for the Army during the war.[46] IBM's reach into computers continued along two lines afterwards. Its more immediate, business-oriented approach involved electronically upgrading its EAM equipment. In September 1946, IBM introduced the 603 Electronic Calculating Punch. It was the first commercial electronic

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[42] Randell, *The Origins of Digital Computers*, 293.
[43] Pugh, *Building IBM*, 81-84.
[44] ASCC is an acronym for Automatic Sequence Controlled Calculator.
[45] Aiken built several other computers at Harvard, including the Mark II, III, and IV. He used electronics in the Mark IV to a limited extent. Paul Ceruzzi, *The Reckoners: The Prehistory of the Digital Computer, From Relays to the Stored Program Concept* (Westport, Connecticut: Greenwood Press, 1983), 43-72; Charles J. Bashe, et al., *IBM's Early Computers* (Cambridge, Massachusetts: MIT Press, 1986), 25-33; Randell, *The Origins of Digital Computers*, 191-192.
[46] These were known as the Aberdeen Relay Calculators. Bashe, et al., *IBM's Early Computers*, 32.

calculator and contained approximately 300 vacuum tubes. Due to unexpected customer interest, IBM limited production to 100 machines and brought out an advanced model. The 604 Electronic Calculating Punch became available in 1948. It contained more than 1,400 vacuum tubes and fifty digits of internal storage. Within ten years, 5,600 had been placed into service. Finally, IBM built the CPC,[47] the ultimate tabulator. It consisted of a 604 Electronic Multiplier connected to a standard IBM accounting machine. It went to market a couple of years before the UNIVAC, which competed against it. The CPC might thus be said to have been the first commercially available computer, even if not a true computer. While the UNIVAC had greater capabilities generally, over 700 CPC systems were in service by the mid-1950s compared to fourteen UNIVAC systems.

IBM did a lot with EAM equipment after World War II, but simultaneously continued the experimental work in supercomputing for scientific applications begun with the ASCC. Its next project was the SSEC, built entirely within IBM and completed in early 1948. The SSEC contained 12,500 vacuum tubes, 21,400 relays, and storage for 3,160 digits in intermediate- and high-speed memory. It gave IBM crucial patents as the first computer with stored-program capabilities, although it lacked the elegant simplicity of the EDVAC.[48] The SSEC found a major use computing positions of the moon and prepared the tables used in the first manned moon landing.[49]

The success of electronic EAM equipment convinced IBM of the viability of a full-fledged commercial computer. Watson ordered development of one in 1948. Changes at IBM intervened, however. Control was passing from Watson to his son of the same name. The younger Watson has received credit for IBM's move into computers, but that was happening anyway, although perhaps not as energetically. Watson Jr. had greater impact in pushing IBM to accept government money for research. He worried that the huge amounts of money the federal government was dumping into computers might cause IBM to fall behind. With Watson Jr. making the decision, IBM temporarily shelved plans for a commercial computer and shifted focus to scientific machines for government. The change distressed IBM salesmen.

IBM therefore developed the NORC [50] for the Navy. The company received its costs plus one dollar for the supercomputer, which after completion in 1954 was for several years the world's fastest computer. More significant, IBM built the 701 Defense Calculator. The company paid for its

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[47] CPC is an acronym for Card-Programmed Electronic Calculator.

[48] Pugh, *Building IBM*, 72-76, 122-126, 131, 136, 151-155, and 159; Randell, *The Origins of Digital Computers*, 193.

[49] Bashe, et al., *IBM's Early Computers*, 55-57.

[50] NORC is an acronym for Naval Ordnance Research Calculator.

development, but modeled it on the IAS computer and employed von Neumann as a consultant.[51] The Defense Calculator first shipped in 1952 and did well enough that it went through several advanced models and evolved into the 7000 series of transistorized computers. Meanwhile, IBM returned to computers for businesses. The IBM 702 Electronic Data Processing Machine (EDPM) specifically targeted heavy users of EAM equipment. IBM limited production to fourteen machines in favor of the 650 Magnetic Drum Calculator, the first of many enormously popular IBM computer lines beginning mid-1950s.[52]

Considering the demanding business environment in which EAM manufacturers operated—forcing them to continually upgrade technologies—IBM's move to electronic tabulators, and thence, to true computers seems natural and inevitable. World War II was more hindrance than help. For example, IBM might have advanced its position considerably if it had the chance to follow through on a series of contacts initiated before the war. Notably, an IBM laboratory manager wrote to Atanasoff in May 1942 in regard to the ABC: "When your development work has proceeded to a point where you feel that it is proper for representatives of our Company to look over your machine, we would appreciate an opportunity to do so."[53] IBM never did examine the ABC officially.[54] Before that could happen, both IBM and Atanasoff had their efforts shunted into war-related work. Otherwise, IBM might have combined technologies inherent in the ABC, or computer work by others, with its own considerable capabilities and built efficient true electronic digital computers before actual circumstances allowed.

Atanasoff gave calculators and accounting machines thorough consideration before beginning the ABC. Moreover, if he had chosen an institution for its suitability to foster invention of the

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[51] Von Neumann was not hired as a consultant specifically for the IBM 701, however.
[52] Pugh, *Building IBM*, 158-161, 163, 174-178, and 180-183; Bashe, et al., *IBM's Early Computers*, 176-178.
[53] G. H. Armstrong, IBM, letter to J. V. Atanasoff, 21 May 1942. Quoted in Pugh, *Building IBM*, 86.
[54] Unofficially, an IBM representative named Manieri did examine the ABC. He apparently was a low-level or student engineer out of Des Moines. He told Atanasoff that IBM was developing a similar machine, which upset IBM officials when they learned of it. Clement Ehret, Director Market Research, IBM, transcription of letter to J. B. Bayard (Hayward?), Patent Development Supervisor, IBM, 18 December 1940. Charles Babbage Institute, Honeywell Collection (box 3, folder 2); see also, *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Dr. John V. Atanasoff," 916. ISU, Parks "John Vincent Atanasoff Papers" (box 30, folder 6); *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Transcript of Proceedings," 1,889; 1,969-1,970; and 2,303. ISU, Parks, "John Vincent Atanasoff Papers" (box 43).

electronic digital computer, he could have made few wiser selections than ISC. He believed the college had little empathy for his work in computing. He probably did encounter skepticism from faculty and staff, but the concepts and implications of the ABC were radical enough that it might have been the case no matter where he attempted it. Nevertheless, ISC officials supported Atanasoff, notably with a modest amount of money in tough times. Officials may not have understood the principles underlying the ABC, or its implicit purpose of solving complex differential equations, but certainly they grasped the need for improved methods of performing computations. In fact, ISC had a history predating Atanasoff of exploring computing machinery for scientific purposes.

Iowa State researchers had early interest in computational equipment because of their desire to do statistical analysis, increasingly important in biological-related research. Rediscovery of Mendelian genetics around 1900 served as a major spur. According to one observer, scientists at ISC in agriculture, biology, and genetics by the 1920s regularly applied statistics in areas exemplified by the following: "Mendelian ratios, the size of the experimental errors in yield tests or feedlot trials, the growth rates of plants and animals, trends of all kinds, . . . (and) interpretation of a selection experiment." Additionally, economists on campus used statistics for such things as determining supply and demand curves. Statistical methods at ISC and elsewhere were elementary, more applied and descriptive than analytical. Methods emphasized fitting regression lines and calculating averages, dispersions, and simple correlations from total counts, as opposed to more sophisticated techniques that evolved later of drawing inferences from samples.[55] Statistics thus occupied much the same rudimentary position mathematically as physics, but larger quantities of data handled by agricultural scientists and economists caused them to recognize a need for laborsaving calculating aids earlier.

Initial interest at ISC in calculating devices can be traced to Henry A. Wallace, who began promoting new statistical techniques in the early 1920s. At the time, Wallace edited *Wallaces' Farmer*, a well-regarded farm journal based in Des Moines. He had been born on a remote Iowa farm into a distinguished family. His father, Henry C. Wallace, became Secretary of Agriculture under Warren G. Harding and Calvin Coolidge. Wallace himself served as Secretary of Agriculture, Vice President, and Secretary of Commerce, respectively, all under Franklin D. Roosevelt. He also

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[55] Jay L. Lush, "Early Statistics at Iowa State University," in *Statistical Papers in Honor of George W. Snedecor*, ed. T. A. Bancroft (Ames, Iowa: Iowa State University Press, 1972), 211-212, 214, and 219; T. A. Bancroft, "Roots of the Iowa State University Statistical Center: 1914-1950," *Iowa State Journal of Research* 57, no. 1 (August 1982), 3.

produced the first hybrid corn sold commercially, and with partners organized the Hi-Bred Corn Company in 1926.[56] It is known today as Pioneer Hi-Bred International.

In "What is in the Corn Judge's Mind?" published in 1923, Wallace explained how multiple correlation, that is, determination of causal relationships among three or more variables, could be used to analyze the opinions of experts on the most desirable attributes of an ear of corn. Corn judges advised farmers on what ears to retain as seed. Assumed to have common standards, experienced judges were asked to rate ears on six factors for impact on yield. Wallace used the scores to assign each factor a correlation coefficient with a method devised by evolutionary biologist Sewall Wright while at the U.S. Department of Agriculture. Wallace also determined "inter-correlations," and arranged the coefficients in a system of linear simultaneous equations for solution. He then calculated final correlation of the degree to which the judges thought each factor contributed to yield, weighted as a percentage. He compared the results to what he calculated each factor actually contributed after the seed was planted and subsequently harvested, and he identified significant differences. The judges considered length of ear most important, but based on two years data, Wallace found weight of kernel far and away the key determinant of yield.[57] Wallace made a forceful and convincing case for the utility of multiple statistical correlations by such examples.

An alumnus, Wallace maintained close ties with ISC. At the request of its faculty, Wallace organized and taught on campus a special course in statistical methods. The course ran over a series of Saturdays in early 1924 and included lectures on calculation of correlation coefficients, partial correlations, and regression lines.[58] Wallace taught the course by practical example and with use of mechanical calculating machines. In most sessions he used various types of the common desktop calculators. In the final sessions, he borrowed punch-card tabulating equipment from an insurance company and demonstrated it. Tabulating equipment had been invented for compiling statistical data, but Wallace's use for complex calculations was among the first.[59]

An enthusiastic response by course participants prompted Wallace to publish the methods he had demonstrated in *Correlation and Machine Calculation*. The practical guide was co-authored by George W. Snedecor. Snedecor, a physicist by education, had taught statistics at ISC since shortly after joining the Department of Mathematics in 1913. He also did consulting in statistics, mostly with

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[56] John C. Culver and John Hyde, *American Dreamer: The Live and Times of Henry A. Wallace* (New York: W. W. Norton, 2000), 3-4, 36-37, 66-71, and 82-83.
[57] H. A. Wallace, "What is in the Corn Judge's Mind?" *Journal of the American Society of Agronomy* 15, no. 7 (July 1923), 300-304.
[58] Bancroft, "Roots of the Iowa State University Statistical Center," 5.
[59] Randell, *The Origins of Digital Computers*, 130.

scientists in agriculture. Wallace and Snedecor's bulletin explained the fundamentals of correlation through familiar examples and for solution on calculating machines, both desktop and EAM equipment. It demanded prerequisite knowledge only in basic algebra and was distributed worldwide.

Tabulating machines had become common in business and government offices, but ISC did not have such equipment, so Snedecor traveled to an insurance company in Des Moines on Saturdays to perform computations for colleagues. As demand grew for statistical calculations by its researchers, ISC established a Mathematical Statistical Service in 1927 and installed an assortment of calculating machines, including IBM tabulating equipment. The service reorganized in 1933 under Snedecor as the Statistical Laboratory to provide a centralized computing service for the entire college. It is believed to have been among the first such services in the world.

Statistics methodology at ISC received a major boost with visits of several distinguished statisticians. Foremost among them was R. A. Fisher from England. During summer 1931, Fisher lectured about equally on topics selected from his two books, *Statistical Methods for Research Workers* (1925) and *Genetical Theory of Natural Selection* (1930). He also conducted clinic sessions to help scientists with their research. Fisher returned in summer 1936 and taught theory of statistics and design of experiments, having published *Design of Experiments* the previous year.[60]

The year following Fisher's last visit, Snedecor published *Statistical Methods*. The text went beyond descriptive statistics to teach statistical inference.[61] It became quite popular and remained in print through eight editions, the last in 1989. By the time Atanasoff began thinking about the ABC, therefore, ISC had established itself at the forefront in use of both statistical and computational methods. In neither area had ISC contributed to theory, however.

Atanasoff began the ABC after realizing that existing equipment could not handle the large sets of algebraic equations derived from many partial differential equations. Extensive calculations with tabulators had by then become common, however. A watershed year was 1928. Snedecor published an article that year extolling EAM equipment for computation. The Mathematical Statistical Service had been operating for a year, and Snedecor was eager to publicize the variety of research it had aided. He reported that one researcher used tabulating equipment to solve a problem with eight variables. The researcher computed the regression equation and multiple correlation

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[60] Lush, "Early Statistics at Iowa State University," 220-222.
[61] Bancroft, "Roots of the Iowa State University Statistical Center," 4.

coefficients in forty minutes, a significant improvement over that possible with desktop machines.

Snedecor noted that another researcher used the machines at ISC to determine the relationship of grades of college students to the scores they had attained in high school.[62] That problem also interested Benjamin D. Wood, who managed the Bureau of Collegiate Educational Research at Columbia University.[63] In his case, he sought help from office appliance vendors. None offered assistance until he approached IBM, and then he got an overwhelming response. Watson decided Wood's problem provided an opportunity to explore new uses for IBM's equipment. In 1928, therefore, Watson gave three truckloads of standard EAM machines to Columbia, which established the Columbia University Statistical Bureau to house them.

Furthermore, IBM initiated projects to develop special machines for Columbia, including a unique high-capacity tabulator. When Wood requested a device that could automatically score thousands of tests, IBM spent seven years and a large sum of money to develop it. The IBM Type 805 International Test Scoring Machine became generally available in 1937. It generated thousands of dollars of revenue for IBM, although never anything other than a minor product.

His interest piqued, Watson thought of other ways to foster non-traditional uses of IBM machines. As one, IBM opened computational centers for short-term, in-house rental of punched-card equipment. As another example and specifically for scientists and engineers, IBM began offering mathematical tables in pre-punched cards for use with EAM equipment.[64]

The IBM machines at Columbia University attracted many scientists, including Wallace J. Eckert (no relation to J. Presper Eckert). Eckert was an astronomer, and astronomers, like statisticians, dealt with huge quantities of data. Astronomers have observed the heavens and collected data for various purposes since time immemorial. A new purpose arose when ships began sailing far out to sea, since navigation over oceans depended upon precise placing of longitude. Determining longitude meant making calculations based on the moon's position as a function of time. Mariners carried navigation tables giving those positions. Unfortunately, the tables were full of errors because the calculations behind them were devilishly complex, involving interactions of three bodies: the moon, earth, and sun. Newton worked out the rudiments of the equations, actually three

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[62] George W. Snedecor, "Uses of Punched Card Equipment in Mathematics," *American Mathematical Monthly* 35, no. 4 (April 1928), 161-169.

[63] Late in life, Wood and Atanasoff corresponded on their mutual interests in revising the English language. Wood had special interest in a typewriter with six keys that Atanasoff developed for his binary alphabet. See, for example, Ben D. Wood, letter to J. V. Atanasoff, 11 October 1972. ISU, Parks, "John Vincent Atanasoff Papers" (box 2, folder 9).

[64] Cortada, *Before the Computer*, 134.

simultaneous second-order differential equations. Order refers to the highest derivative in the equation, and second-order differential equations are among the most useful. Mathematicians through the eighteenth century worked to improve Newton's equations, which remained difficult to solve. Thus, driven by the urgent need for accurate navigation, astronomers had long sought a mechanized numerical method for performing calculations and placing answers into error-free tables.[65]

Eckert, like Wood, won Watson's backing. For instance, when Eckert designed a "Calculation Control Switch" that synchronized operations of several pieces of standard EAM equipment to perform complex computations, IBM built it for him. Eckert noted as a general observation that although tabulating equipment had wide application in business and statistics, its use in science was limited to astronomy. (He apparently categorized work at ISC as statistical.) However, he claimed that various EAM equipment existed for "practically all purposes," and "with slight modifications" was "ideal for scientific work," including numerical integration and differentiation. "The main question in any case," he wrote effusively in a 1940 publication, "is not 'can the problem be solved by these machines?' but rather 'have I enough operations of this type or that to justify such powerful equipment?'"[66]

Eckert gained wide recognition for expertise in digital computing applications, and being such an enthusiastic cheerleader for its equipment, prompted IBM in 1933 to provide funding to establish a computing laboratory in Columbia's Department of Astronomy. The laboratory became the Thomas J. Watson Astronomical Computing Bureau.[67] Then, as World War II wound down, Eckert became the first scientist employed at IBM. The company hired him to establish specifications for the SSEC, no doubt explaining its calculations on the positions of the moon.[68]

Eckert was not first to perform astronomical calculations on punched-card equipment, however. That distinction belongs to Leslie J. Comrie, Superintendent of the Nautical Almanac Office of the Royal Naval College in England. He initially explored desktop machines and explained in a 1925 article why scientists had not made much use of them. The first reason was their high cost and poor reliability. However, Comrie reported that prices were falling and quality improving. The

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[65] Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, New Jersey: Princeton University Press, 1972), 27-30; Eckert, *Punched Card Methods in Scientific Computation*, 2.
[66] Eckert, *Punched Card Methods in Scientific Computation*, iii, 1, 8, and 43; Bashe, et al., *IBM's Early Computers*, 23-24.
[67] Goldstine, *The Computer from Pascal to von Neumann*, 109.
[68] Pugh, *Building IBM*, 67-72 and 123-126.

second reason was the inadequacy of numerical procedures. Finally, Comrie noted that the poor quality of mathematical tables was itself a cause for slow acceptance of mechanized calculations. That is, scientific calculations often incorporated mathematical values that were themselves laborious to calculate, compounding the overall difficulty.[69]

In 1928, the watershed year, Comrie discovered tabulating machines. In particular, he found them a powerful tool for creating tables. As discussed, most values in mathematical and astronomical tables did not come directly from fundamental formulae; that took too much effort. Instead, a relatively few pivotal values were derived from basic formulae to create a framework from which to estimate intermediate values by interpolation with simpler formulae. Despite Eckert's exuberant claims, tabulating machines could not conveniently obtain pivotal values in many cases. Tabulators proved adept at interpolating, however.[70]

Even if large calculations were not easily within the capacity of EAM equipment, Comrie demonstrated that it nevertheless could do them and provided substance to Eckert's claims. In particular, Comrie won international attention for computations on the orbits of the moon using data from Ernest W. Brown's *Tables of the Motion of the Moon*. Brown, who happened to be Eckert's former professor at Yale, had produced especially accurate tables.[71] Using them was no easier for that, however. The Nautical Almanac Office dedicated the continuous labor of two (human) "computers" to the task. Comrie decided to reduce overall human involvement by using EAM equipment to compute the harmonic functions by time, the most labor-intensive part of the calculations. Making the calculations for twenty years into the future took thirteen months and half a million cards. Just punching the cards took six months. The superior results Comrie obtained at a fraction of the costs of manual computation made the project worthwhile and influenced other scientists to attempt similar large calculations. In particular, it set a precedent for the daunting first problem for the ENIAC, the calculations for the hydrogen bomb, which took several months and one million cards.

Indeed, the two projects some fourteen years apart gives perspective to computing progress. Even if electromechanical, a prewar tabulator calculated similarly to ENIAC. That is, both fundamentally computed by counting with decimal numbers. Thus, numbers of cards provides a rough comparison of the relative complexity of the two problems involved. All this suggests that the

[69] L. J. Comrie, "The Application of Calculating Machines to Astronomical Computing," *Popular Astronomy* 33 (1925), 243-244.
[70] L. J. Comrie, "On the Construction of Tables by Interpolating," *Monthly Notices of the Royal Astronomical Society* 88, no. 6 (13 April 1928), 506 and 518-519.
[71] Goldstine, *The Computer from Pascal to von Neumann*, 108-109.

ENIAC may have been on the order of five to twenty times as powerful a calculator as the tabulator that Comrie used, an older model designed for 45-column cards.[72] The ENIAC is said to have been 500 to 1,000 times faster than the best electromechanical computers, such as the ASCC.[73] However, that estimate comes from comparing computational rates in operations per second. In overall performance—the more meaningful comparison—differences were probably negligible, as Comrie's use of comparatively antiquated equipment demonstrated.

In 1940, when Atanasoff wrote an explanatory manuscript to accompany applications for funding to complete the ABC, he listed nine examples of problems the computer could help solve. The first three, multiple correlation, curve fitting, and method of least squares, dealt ordinarily with statistics, although the latter could refer to an approximate solution method of differential equations (the Boussinesq method).[74] Atanasoff's placing of statistics-related uses as highest priority might suggest substance to a hoary rumor at Iowa State that a word from Wallace gave the inspiration for the ABC. Atanasoff did not arrive on campus until after the 1924 statistics course but did meet Wallace briefly. He also attended lectures by Fisher and knew him well enough to pay a social visit when in England. While Wallace and Fisher impressed Atanasoff, he claimed neither man had direct impact on the ABC.[75] The specific priority in the listing of uses for the ABC, according to him, reflected less his interests than it did the ISC environment, which of course was influenced by Wallace and Fisher.[76]

Atanasoff had long been interested in calculating devices, in fact. As a boy in Florida, along with his fascination with the slide rule, he read articles on computing machines in *International Encyclopedia* and explored various types of desktop calculators in the offices of his father's employer,

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[72] L. J. Comrie, "The Application of the Hollerith Tabulating Machine to Brown's Tables of the Moon," *Monthly Notices of the Royal Astronomical Society* 92, no. 7 (13 May 1932), 694, 697-700, and 706; Randell, *The Origins of Digital Computers*, 130.

[73] Brian Randell, "Colossus: Godfather of the Computer," in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 353; Goldstine, *The Computer from Pascal to von Neumann*, 117.

[74] John V. Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," in *The Origins of Digital Computers: Selected Papers*, ed. Brian Randell, 3rd ed. (New York: Springer-Verlag, 1982), 315.

[75] J. V. Atanasoff, New Market, Maryland, transcript of interview with Uta C. Merzbach, 5 May 1969, 42-44; J. V. Atanasoff, New Market, Maryland, transcript of interview with H. Tropp, 24 May 1972, 105-111; John V. Atanasoff, New Market, Maryland, transcript of interview with B. Kaplan, 23 August 1972, 74-76. Smithsonian.

[76] *Honeywell*, "Transcript of Proceedings," 2,141-2,157; John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 18 February 1972, 11-14. Smithsonian.

Amalgamated Phosphate Company.[77] At ISC for a Master's, he did little serious computing but enjoyed hanging around the Mathematical Statistical Service, located for a time in the Physics Building.[78] His first taste of truly demanding machine-assisted calculations came as he labored over his dissertation at the University of Wisconsin. The frustrating experience gave Atanasoff an appreciation of a need for better calculators.

Several years after returning to ISC with his doctorate, Atanasoff tested the capabilities of EAM equipment by analyzing complex spectra.[79] The spectra of radiation emitted by electrons correspond to their energy levels, or rather, changes in energy levels as they jump among possible orbits. Spectra analysis depended then upon tedious cut-and-try methods. One common procedure involved plotting frequencies of radiation lines on long strips of paper and using dividers to isolate equally spaced pairs of lines representing energy levels. Atanasoff had therefore chosen a problem important to quantum mechanics, but his larger purpose was to explore the potential of tabulating equipment.

Atanasoff's method involved recording frequency data in punch cards and having a tabulator and sorter identify corresponding energy differences. An IBM tabulator did not have sufficient capacity to do the job unaided, however. Moreover, IBM only leased its equipment and did not permit modifications. Atanasoff therefore invented an attachment to extend the capabilities of a tabulator without altering it. Remarkably, he made his design without a full understanding of the inner workings of the tabulator. IBM jealously guarded that information. Atanasoff learned what little he could from the local IBM service representative and guessed on other pertinent details. The arrangement satisfactorily handled the analysis, and Atanasoff used it to analyze one or two spectra. A. E. Brandt, an ISC statistician and experienced EAM equipment hand, assisted in the project, largely by procuring information and parts from IBM, with which he enjoyed especially cordial relations.[80]

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[77] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 49-51 and 54-55; Atanasoff, interview with Merzbach, 5 May 1969, 17-18.

[78] Lush, "Early Statistics at Iowa State University," 221.

[79] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 133.

[80] J. V. Atanasoff and A. E. Brandt, "Application of Punched Card Equipment to the Analysis of Complex Spectra," *Journal of the Optical Society of America* 26, no. 2 (February 1936), 83-88; Atanasoff, interview with Merzbach, 5 May 1969, 63-69 (actually unnumbered); Atanasoff, interview with Tropp, 24 May 1972, 108-110; Atanasoff, interview with Kaplan, 23 August 1972, 7-8 and 72-74; John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 17 April 1972, 35-36; J. V. Atanasoff, transcript of interview with B. Kaplan, Smithsonian Institution, 17 July 1972, 11-14; John V. Atanasoff, transcript of interview with Bonnie Kaplan, Smithsonian Institution, 10 August 1972, 23 and 32-35. Smithsonian.

With his success enlarging the capacity of an IBM tabulator for analysis of complex spectra, Atanasoff decided to extend the machine further to aid with the more pressing and difficult problems his students faced.[81] By the mid-1930s, they were already being constrained by the limited available capabilities for solving linear algebraic equation sets. However, Atanasoff offered to sell patent rights to his design to IBM rather than build another attachment. "I have good reasons to believe," he claimed in a letter to the company, "that this method will solve systems of equations with nine unknowns in one-tenth or less of the time needed by the methods used at present and do this with the accuracy and absence of fatigue of a fully mechanical method." By "this method," Atanasoff meant use of his proposed attachment and IBM tabulator.

Besides a desire to sell his idea, Atanasoff had a personal purpose for telling IBM of his invention. He wanted to demonstrate that he was "not a too academic sort of person," because he wanted to work for the office appliance company. "I am interested in the possibilities of mechanized mathematics," he explained to an IBM official, before adding prophetically, "and your organization seems destined to play a dominant role in this field."[82] He admitted that a second reason he wanted a job change was that the possibility of promotion at ISC seemed remote.[83] However, he made clear that he would be leaving ISC on good terms and listed the heads of the mathematics and physics departments among his references.[84]

To the question on the IBM job application form: "What is your formula for success?" Atanasoff characteristically emphasized his propensity for hard work: "Work long and earnestly." Some colleagues did not credit him with a sense of humor (indeed, he did not credit himself with one), but he then added tongue-in-cheek: "Choose four able grandparents. Hope that they transmit to you, as well as ability, a bit of humor to avoid a wreck on the rocks of adversity."[85]

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[81] Atanasoff, interview with Kaplan, 23 August 1972, 29-30.
[82] John V. Atanasoff, copy of letter to W. W. McDowell, IBM, 27 March 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).
[83] John Vincent Atanasoff, IBM "Application for Employment," 25 January 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).
[84] John V. Atanasoff, letter to W. W. McDowell, IBM, 27 January 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 24, folder 4).
[85] John Vincent Atanasoff, (IBM) "Employment Questionnaire," 25 January 1937; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 10 July 1968, 17. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 4, and box 26, folder 2).

IBM did not offer a job to Atanasoff, either then or to inquiries he made to World War II.[86] That seems a mistake. However, IBM did not do scientific research *per se*. Atanasoff claimed, quite honestly, "an easy working knowledge of mechanisms and a clear understanding of electronics and other applications of electricity." On the other hand, IBM probably did not know what to make of a job applicant who admitted that his, "experience has been mostly obtained in the teaching field,"[87] who specified employment as a "Research Mathematical Physicist,"[88] and who demanded, "considerable liberty in doing research work."[89] As noted, IBM hired Wallace Eckert for a specific project toward the end of the war, thereby selecting as its first scientist someone with whom it already had a close relationship.

As for Atanasoff's offer to sell his design for a tabulator attachment for solving simultaneous equations, IBM gave it fair consideration but declined. The company naturally was curious and asked for more information, since Atanasoff had disclosed only generalities. To protect itself and Atanasoff, IBM recommended that he send a patent application, cautioning: "It is our experience . . . that persons who may be working quite independently of one another often conceive ideas which are essentially alike."[90] Multiple inventors devising the same invention is a surprisingly common phenomenon, and IBM recognized the real possibility of it already having rights to a similar device. Atanasoff had not applied for a patent, but in place of an application, sent notarized copies of a drawing and a short descriptive manuscript.[91] IBM engineers looked over the materials and were impressed. Nonetheless, they found the information insufficient to give the device a thorough

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[86] W. W. McDowell, Assistant to Vice President, IBM, letter to John V. Atanasoff, 6 April 1937; John V. Atanasoff, copy of letter to Clement Ehret, Director of Market Research, IBM, 5 July 1940; John V. Atanasoff, copy of letter to J. B. Hayward, IBM, 22 April 1941; J. B. Hayward, IBM, letter to John V. Atanasoff, 24 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2). Atanasoff also applied to General Electric for a summer job to gain industrial experience. Again, he was turned down. John V. Atanasoff, copy of letter to Mr. A. R. Stevenson, Engineering General Department, General Electric, 1 March 1938; M. M. Boring, General Electric, letter to John V. Atanasoff, 15 March 1938. ISU, Parks, "John Vincent Atanasoff Papers" (box 12, folder 5).

[87] John V. Atanasoff, copy of letter to Harry Titus, Vice-President, IBM, 14 January 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

[88] Atanasoff, "Application for Employment," 25 January 1937.

[89] Atanasoff, letter to McDowell, 27 March 1937.

[90] Clement Ehret, Director of Market Research, IBM, letter to John V. Atanasoff, 29 April 1937. Charles Babbage Institute, Honeywell Collection (box 1, folder 5).

[91] John V. Atanasoff, copy of letter to Clement Ehret, Director of Market Research, IBM, 17 June 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2); John V. Atanasoff (attributed), "Solution of Systems of Linear Equations by the Use of Punched Card Equipment," circa 1937. Charles Babbage Institute, Honeywell Collection (box 1, folder 4).

evaluation. IBM thus wrote back to Atanasoff insisting that it needed the patent application.[92] In fact, although not told to Atanasoff, the engineers were not as interested as they might have been, because they believed IBM already possessed a patent on technology that could solve simultaneous equations in a slightly different way.[93]

Atanasoff was deeply disappointed, both at IBM's refusal to hire him and its seeming lack of interest in his invention. He complained to Theodore H. Brown, Harvard business professor and consultant to IBM (and who had introduced Howard Aiken to James Bryce, leading to the ASCC), that he suspected the company simply did not understand the scientific importance of solving systems of algebraic systems.[94] However, he took IBM's advice and had a law firm search for related patents as a first step for an application.[95] The firm, Dieterich and Rutley, sent him copies of several. The most pertinent was one by Bryce and was probably the patent the IBM engineers thought applicable for solving sets of linear algebraic equations.[96] After Atanasoff reviewed it and the other patents, he decided his idea had novel aspects.[97]

Even so, Atanasoff decided against pursuing a patent. He came to realize that the capabilities of even the best tabulators simply could not be expanded cost-effectively to solve the large sets of equations the work of his students demanded.[98] Atanasoff's rule-of-thumb was that the difficulty of solving a set of linear equations varied roughly as the cube of the number of unknowns. Actual difficulty varied depending on accuracy required, but generally as the number of unknowns increased,

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92 Clement Ehret, Director of Market Research, IBM, letter to John V. Atanasoff, 16 September 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

93 Patent Department (unsigned), IBM, copy of memorandum on "Solution of Linear Algebraic Equations by Punched Card Method J. V. Atanasoff" to C. Ehret, Director Market Research, IBM, 7 September 1937. Charles Babbage Institute, Honeywell Collection (box 1, folder 5).

94 John V. Atanasoff, copy of letter to Theodore H. Brown, Harvard Business School, 12 August 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20); Bashe, et al., *IBM's Early Computers*, 25.

95 John V. Atanasoff, copy of letter to Dieterich and Rutley, Washington, D.C., 18 September 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

96 Albert E. Dieterich, Patent Attorney, Dieterich and Rutley, copy of letter to John V. Atanasoff, 29 September 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

97 John V. Atanasoff, copy of letter to Albert Dieterich, Patent Attorney, Dieterich and Rutley, 18 October 1937. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

98 *Honeywell*, "Deposition of Dr. John V. Atanasoff," 146-148; Atanasoff, interview with Merzbach, 5 May 1969, 85-86 (actually unnumbered); Atanasoff, interview with Tropp, 17 April 1972, 34 and 37-39; Atanasoff, interview with Kaplan, 10 August 1972, 34; Atanasoff, interview with Kaplan, 23 August 1972, 21-22.

so did need for accuracy.[99] Atanasoff was already anticipating the need to solve sets in twenty or more unknowns, far beyond what he could hope to do with a tabulator, at least at reasonable cost.

Unwilling to give up, Atanasoff was therefore forced to consider ways to contrive a more powerful computing mechanism. One idea was to gang thirty or so mechanical calculators together on a common shaft to operate as one huge machine. Coefficients from a pair of equations were to be entered manually into consecutive calculators, and all machines operated in unison to eliminate one variable. After the results were recorded manually, the process would be repeated with another pair of equations, over and over, until all variables were identified.[100] Atanasoff recognized the process as arduous and error prone, but desperate, asked Dieterich and Rutley to conduct a patent search on the concept.[101] The search evidently turned up nothing, but even so, Atanasoff also discarded the ganged-calculator idea as impractical. Buying so many calculators involved more money than he could hope to find, and in any case, calculators had insufficient accuracy for his needs. Furthermore, getting numbers in and out of the calculators looked too difficult.[102]

EAM equipment had greater capabilities than normally acknowledged, but it nevertheless could not handle many computational problems of interest to researchers. Furthermore, a different type of computing mechanism existed, more powerful in some respects, but not accurate enough for Atanasoff's purpose. The two categories of computers are digital and analog, but the distinction became clear only about World War II, coincident with acceptance of the terminology. Atanasoff himself apparently coined the word analogue, meaning analog devices. His terms for digital mechanisms were either pulse,[103] when electronic, or awkwardly, "computing machines proper."[104] Other terms for digital calculators were numerical, arithmetical, or discrete calculating machines.[105]

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[99] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 316; *Honeywell*, "Deposition of Dr. John V. Atanasoff," 143-144.
[100] Atanasoff, interview with Merzbach, 5 May 1969, 83-84 (actually unnumbered); Atanasoff, interview with Tropp, 17 April 1972, 39-43; John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 24 April 1972, 4-7. Smithsonian.
[101] Atanasoff, letter to Dieterich and Rutley, 18 September 1937.
[102] Atanasoff, interview with Merzbach, 5 May 1969, 84 (actually unnumbered).
[103] See for example, John V. Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDCrc 143," 7. National Archives.
[104] John Vincent Atanasoff, "Advent of Electronic Digital Computing," *Annals of the History of Computing* 6, no. 3 (July 1984), 234.
[105] See for example, J. A. Rajchman, "RCA Computer Research: Some History, and a Review of Current Work," *RCA Engineer* 8, no. 6 (April/May 1963), 6.

The mechanical and electromechanical tabulators and desktop calculators were not computers but digital machines whose essential operation involved counting with decimal numbers. Digital mechanisms existed long before desktop calculators, however. The abacus is a digital device of ancient origin. Indeed, digital calculation aids have been around as long as people have used ten digits, that is, fingers, to count. Perhaps for that reason, digital computers have been said to be those that perform computations by counting. That was true of the ENIAC but not the ABC or modern digital computers generally.

A fundamental distinguishing trait is that all electronic digital devices depend upon operational signals of discrete voltage pulses. The valleys and peaks are typically referred to as zeros and ones. A relative high voltage is described as a one and a low voltage a zero, or vice versa. Atanasoff and Berry adopted the opposite convention, now called negative logic.[106] Either way, all information a digital computer needs to perform its myriad functions is encoded within infinitely variable strings of binary voltages. Specific patterns can represent decimal numbers, letters of the alphabet, or other identifiable symbol. Moreover, as noted, digital signals can be manipulated to perform binary arithmetic and, thence, to approximate operations in higher mathematics through numerical methods.

Analog computers are harder to define, yet more descriptive of their name. While a digital signal has only two important states, high or low, or on or off, all conditions in an analog signal are meaningful. Instead of being fundamentally discrete, analog signals are continuous—like the world we perceive. An analog computer represents numbers through some system of physical measurements and is directly analogous to the problem it was created to solve.[107] That is, a mathematical equation is analogous to the physical phenomenon it models, and in turn, an analog computer is analogous to the mathematical expression it represents.

A slide rule is an example of an early analog calculating device. In fact, slide rules were the most common form of calculating device used by scientists and engineers into the 1960s. However, analog computers far more advanced than slide rules were already established before Atanasoff began the ABC. Analog computers never had the versatility, power, or accuracy that electronic digital computers eventually came to have but could handle many mathematical problems. They are still used in specific applications.

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[106] Alice R. Burks and Arthur W. Burks, *The First Electronic Computer: The Atanasoff Story* (Ann Arbor, Michigan: University of Michigan Press, 1988), 297; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 9 July 1968, 3. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 5).

[107] Goldstine, *The Computer from Pascal to von Neumann*, 39-40.

Atanasoff naturally experimented with analog computing mechanisms along with digital ones. One idea was to create a super-accurate slide rule from 35mm film stock. He planned to wind the film around sprockets mounted in a framework about the size of a desk. Displacement of the slides provided the readings on a typical slide rule, but because film stretches, Atanasoff intended to take measurements from the rotations of the sprockets as their teeth meshed with holes in the film. Moreover, the device was to have multiple, interconnected slides for better accuracy. While a normal slide rule was good to 1 part in 2,500, Atanasoff thought his deluxe model might have accuracy as high as 1 part in 250,000.[108]

Atanasoff did not build a super-slide rule, but he and graduate student Lynn Hannum fabricated a modeling device to solve a common second-order partial differential equation called Laplace's equation. They named their device a Laplaciometer. It was based on an earlier one that created a physical model of a differential equation in soap film. Atanasoff and Hannum chose paraffin for its advantages for stability and permanence.[109] Thus, the Laplaciometer shaped 100-pound blocks of paraffin into the physical embodiment of the solution to Laplace's equation. Atanasoff demonstrated that the Laplaciometer could solve torsion problems to get answers to within 2 percent of theoretical values.[110] Additionally, Atanasoff built a special analog calculator to estimate the "granularity index" of photographs, another area of research.[111]

The partial differential equations that Atanasoff and his students faced could not be solved by conceivable analog methods, but in fact, the first computers with the capability to handle ordinary differential equations were analog machines called differential analyzers. They evolved from the 1920s through World War II largely under Vannevar Bush at MIT. Son of a Boston Universalist minister, Bush taught electrical engineering, which became mathematically complex early in the twentieth century. The first electrical circuits were direct current (dc) and comparatively easy to

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[108] Atanasoff, "Advent of Electronic Digital Computing," 234-235.
[109] Lynn Albert Hannum, "Approximation to Solutions of Poisson's Equation by Means of Geometrical Models," unpublished Master's thesis, Iowa State College, Ames, Iowa, 1940.
[110] Glenn Murphy and J. V. Atanasoff, "A Mechanical Device for the Solution of Equations Involving the Laplacian Operator," *Iowa Engineering Experiment Station Bulletin 166* 48, no. 25 (16 November 1949); Atanasoff, interview with Merzbach, 5 May 1969, 70 (actually unnumbered); Atanasoff, interview with Tropp, 17 April 1972, 25-29; *Honeywell*, "Transcript of Proceedings," 1,657-1,662 and 2,374-2,378.
[111] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Action No. 15,823 and No. 15,824, "Deposition of Dr. John Vincent Atanasoff," 11. ISU, Parks, "John Vincent Atanasoff Papers" (box 20, folder 1).

analyze. Algebra did fine. Alternating current (ac) circuits gained popularity from the late nineteenth century, because they are more efficient and cost effective in many applications, particularly those involving transmission over long-distances. Alternating current constantly changes direction, so its rigorous description requires differential equations. Furthermore, design considerations forced engineers to account not only for steady-state (if continually changing) conditions, but also for transients introduced from short circuits, activation of switches, and other disturbances too critical to ignore. Transients added significant complexity to equations.

As noted, differential equations are easier to develop than solve analytically. Because mathematicians disdained applications before World War II, engineers investigated solution methods themselves.[112] Bush earned his Ph.D. at MIT attempting to transform certain differential equations into algebraic ones based on techniques of mathematician Oliver Heaviside. Not understanding applied mathematics particularly well themselves, Bush's professors failed to catch a major error in his dissertation.[113]

With a huge growth in telephone and electrical services, the problem of analyzing ac circuits became critical by the 1920s. The high costs of building and operating long-distance networks meant utilities could ill afford failures. As an analog approach to the problem, MIT began considering ways to model large networks in the laboratory.[114] One method entailed solution of simultaneous algebraic equations through use of an electrical replica called the Network Analyzer, associated in particular with Harold Hazen, a former student of Bush.[115] Another line of inquiry led Bush to differential analyzers.[116]

Despite their name, differential analyzers solved not differential equations, but integral equations. Mechanisms to perform integration were readily available, but no satisfactory differentiators existed. Fortunately, differentiation and integration are inverse operations, so an

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[112] Susan Puchta, "On the Role of Mathematics and Mathematical Knowledge in the Invention of Vannevar Bush's Early Analog Computers," *IEEE Annals of the History of Computing* 18, no. 4 (1996), 50-51.

[113] G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: The Free Press, 1997), 31-32.

[114] Larry Owens, "Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, eds. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 6.

[115] Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882-1982* (Cambridge, Massachusetts: MIT Press, 1985), 96-103.

[116] V. Bush, "The Differential Analyzer: A New Machine for Solving Differential Equations," *Journal of the Franklin Institute* 212, no. 4 (October 1931), 448-449.

equation in one form can be transformed to the other, although often not perfectly.[117] To solve a differential equation on a differential analyzer, it was therefore rephrased in integral form.[118]

Actually, the immediate ancestor of the differential analyzers was created to solve a particular integral equation. John R. Carson, a transmission engineer at AT&T, developed an integral formula for the response of an electrical network to a suddenly impressed voltage. The formula provided critical stability information, but like many differential equations, was too complex to calculate analytically. Engineers instead solved it through labor-intensive graphical methods. Seeking something more convenient, Bush and graduate students H. R. Stewart and F. D. Gage invented a mechanism in 1925 whose central component was a dc watt-hour meter, which did integration in ordinary operation. Hazen, then a student, added a mechanical wheel-and-disc integrator to create an integraph that solved second-order differential equations. Bush and his students called the device the Continuous or Product Integraph.

A wheel-and-disc integrator included a metal wheel that both rolled over a rotating glass disc and slid across its radius. The two actions allowed the wheel to trace a curve, which the integrator transformed into an output via a rotating shaft analogous to defining an area. It thus performed integration, because finding an area under a curve is precisely what integration entails. The Product Integraph immediately prompted comparisons to the human brain. In a front-page article, *The New York Times* dubbed it a "Thinking Machine,"[119] a stigma computers still carry.

With the Integraph proved viable, Bush began a more "comprehensive" machine in 1928 with money furnished by MIT. He may not have known, but somewhat similar devices had been built before. Notably, British physicist Lord Kelvin created a harmonic tide analyzer in the 1870s, and American Hannibal Ford devised an integrator for aiming battleship guns in 1919.[120]

Still, the Differential Analyzer was a remarkable machine. A disc integrator was simpler and more precise than a watt-hour meter, so Bush abandoned the latter and incorporated six of the former. That allowed the Analyzer to solve sixth-order differential equations, a capability selected because of the "frequency with which problems are encountered involving two or three simultaneous second-order equations." To prevent slippage within the integrators, which contributed to inaccuracy, Bush

[117] That is, differentiation of a function yields a specific function, but antidifferentiation, or integration, yields a function including an unknown constant.
[118] V. Bush and S. H. Caldwell, "A New Type of Differential Analyzer," *Journal of the Franklin Institute* 240, no. 4 (October 1945), 259.
[119] Quoted in Owens, "Vannevar Bush," 3.
[120] Zachary, *Endless Frontier*, 49.

installed a mechanical torque amplifier with each. Other major components included electrical motors, gears, and shafts, all mounted in a large horizontal framework.

Bush described the Differential Analyzer as follows: "a machine in which the values of the variables involved are represented by the positions of rotating shafts. These shafts are interconnected by mathematical units which force them to move in accordance with the functional relations expressed in the equation." That is, the components of the Differential Analyzer were bolted together to simulate the equation being solved. One computer historian noted that the machine, "did not so much compute as kinetically act out the mathematical problem." Each equation required a unique arrangement of components, so the form of the Analyzer changed for every problem solved. Interconnections could be quite complex. The solution of simultaneous differential equations, in particular, involved numerous "feedback connections."

Operators used input boards to trace curves as input to the Differential Analyzer. Planetary differential gears added and subtracted. Spur gears multiplied by constants. Otherwise, multiplication depended upon a calculus technique called integration by parts.[121] Integrators did integration, of course. All components were linked through rotating shafts, and solutions emerged as displacements of output shafts. The Analyzer converted the displacements to graphs on paper. The areas contained within the graphs gave final answers.[122]

The characteristics of the Differential Analyzer allowed it to solve integral equations directly. It was not adept at arithmetical operations, however. As noted, a digital computer has the opposite traits. It does arithmetic rather naturally, and doing that, can contrive solutions to mathematical operations numerically.

Starting in the early 1930s, the Differential Analyzer solved ordinary differential equations successfully within its limitations. It arguably represented the most advanced computing technology of its day, and a number of copies were built, including a few outside the United States. Some believed that the future of computing belonged to such devices.

To grasp more of that potential, Bush built a more powerful analog computer. He turned to Warren Weaver for funding. Atanasoff's former professor had left the University of Wisconsin in 1931 to become director of the Natural Sciences Division of the Rockefeller Foundation. Weaver went to see the Differential Analyzer and left quite impressed. Thus, in 1935, the Rockefeller

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[121] Arthur W. Burks, "From ENIAC to the Stored-Program Computer: Two Revolutions in Computers," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 323.

[122] Owens, "Vannevar Bush," 7-11 and 14; Bush and Caldwell, "A New Type of Differential Analyzer," 255-259 and 269; Bush, "The Differential Analyzer," 451.

Foundation gave Bush $10,000 to study the possibility of an advanced analyzer. The next year, it presented him with $85,000 for construction.

The Rockefeller Analyzer weighed approximately one hundred tons. Its essential elements remained those of the Differential Analyzer, but there were more of them, and they performed with greater precision and flexibility. Components included eighteen mechanical integrators and some 150 electric motors. So much hardware gave the new analyzer a capacity to solve several problems simultaneously but also made elaborate and troublesome controls necessary. Many of the controls were electrical or electronic. The Analyzer contained some 2,000 vacuum tubes, used in such things as ten "high-speed" numerical counters, which were actually mostly mechanical. The automatic controls of the Rockefeller Analyzer included programming capabilities via three punched-paper tapes. Output could take the form of graphs, or more often, data in printed tables.[123] The Rockefeller Analyzer finally began regular operation in 1942, about three years behind schedule. Immediately conscripted by the military for calculating ballistics tables and radar antenna profiles, its existence was not disclosed publicly until 1945.

Bush received promotions to dean of engineering and vice-president of MIT. He left in 1939 to become president of the Carnegie Institution of Washington, the largest private prewar funding source for research in the nation. While still at MIT, he moved the Carnegie Corporation to donate money to create a Center of Analysis on campus as a locus for fund raising for development of information-processing devices. The center also housed the machines, including the Rockefeller Analyzer. The director was Samuel Caldwell, who had been Bush's student and became his chief lieutenant on computing.

MIT researchers had special interests in microfilm, photoelectricity, and electronics, so Bush explored ways to exploit those technologies under the auspices of the center. The Navy gave him funding to develop a cryptanalytic machine as one project. It wanted something faster at cracking coded messages than the EAM equipment it used. Bush therefore designed the Comparator, a machine comprised of the three technologies and intended to decipher cryptic messages at high speeds by statistically analyzing the occurrences of letters.

The Comparator probably represented the first attempt to incorporate electronic counters into a computational device. Unfortunately, the counters did not work well. The project ran into other

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[123] Owens, "Vannevar Bush," 3, 15-17, and 32; Bush and Caldwell, "A New Type of Differential Analyzer," 276-278, 296-298, 311, and 326.

technical problems, and Bush abandoned microfilm data storage for paper tape. Worse, he became overextended. Forced to choose between projects, he directed most of the Center's resources to the Rockefeller Analyzer. The neglected Comparator failed to work when delivered to the Navy, which packed it away and suspended further efforts to develop cryptanalytic devices in the crucial years before the war.

Washing his hands of the Comparator and behind schedule on the Rockefeller Analyzer, Bush nonetheless kept related projects going. Concerned with growth in printed materials, he saw a need for a Rapid Selector for tracking information important to scientists. The advanced storage and retrieval system was to search coded reels of microfilm at operational speeds about 150 times that of a tabulator. Frames of information could then be selected for printing. NCR and Eastman Kodak gave Bush $25,000 for the project. His students finished a version of the Selector in 1940, after he left MIT. It turned out larger, slower, and more expensive to operate than Bush anticipated. Manual library-card files actually performed better. Consequently, MIT found no sponsor for the Selector's further development, so it was abandoned like the Comparator.

In 1941, Bush was appointed to head the National Defense Research Committee (NDRC) and given wide latitude to dispose of the public's money. He moved the Comparator out of storage and refurbished it for the Navy, which got some limited use from it. Bush spent more money on an advanced Comparator, which failed. The Selector, too, was taken from storage, modified for code breaking, operated briefly, and shut down forever. The Navy finally had enough, and over Bush's protests, took charge of its efforts to develop cryptanalytic machines. It contracted with NCR and Gray Manufacturing Company to construct some twenty code-breaking machines based on technologies similar to those of the Comparator. According to one historian, the Navy spent as much money developing such devices as the Army did on the ENIAC.

Just how well the Navy's cryptanalytic equipment worked seems a matter of opinion. So great was the need that researchers from the Navy formed ERA after the war and continued investigating the technologies. Various other efforts also tried to perfect a Comparator or Selector using government money. Perhaps the most successful Selector-like machine was one for the Navy's Bureau of Ships. By its completion in the early 1960s, electronic digital computers had rendered it obsolete.[124]

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[124] Colin Burke, "A Practical View of Memex: The Career of the Rapid Selector," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, eds. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 145-161; Zachary, *Endless Frontier*, 270-276.

While the Differential Analyzer, Comparator, and Rapid Selector are relegated to obscurity, a related machine, Memex,[125] has attained cult status. "As We May Think," the popular article in which Bush described it, has been reprinted often but first appeared in *Atlantic Monthly* and *Life* magazines in 1945.[126] Because of that date, inspiration for the futuristic information-processing machine has been assumed rooted in World War II. In fact, Memex was a product of the same times and thinking as the Comparator and Rapid Selector. Similar concepts appeared earlier in Europe, notably by H. G. Wells, the British science fiction writer.[127] First documentation of Memex was in a memorandum that Bush sent to Weaver in 1937. Then in 1939, soon after leaving MIT, Bush wrote an unpublished essay, "Mechanization and the Record," providing a detailed description.[128]

Bush conceived of Memex as a mechanical extension of the brain. Like the Rapid Selector, Memex depended upon microfilm, with which, "The *Encyclopaedia Britannica* could be reduced to the volume of a matchbox" at a cost of a nickel for materials. Thus, a "library of a million volumes could be compressed" into Memex. Images of documents and photographs were to be transferred to microfilm with a scanner-like device. Also involved were a tiny "Cyclops" camera to be worn on the user's head for taking microphotographs and a "Vocodor,"[129] with which spoken words could be transformed to type: "The author need not write—he could talk his thoughts to a machine." Memex could quickly select and retrieve stored documents and a screen allowed their viewing. Finally, Memex could perform logical and arithmetic operations using digital technology. In short, Memex compared to a personal computer. It looked something like one: it was about the size of a desk and had a keyboard and monitor but could also be operated remotely by radio.[130]

Bush never built Memex, and considering the poor ends of the Comparator and Rapid Selector, it was probably well he did not try. However, his vision served as a guide to creators of personal computers, E-mail, and the Internet. Key figures in the development of those technologies,

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[125] Memex stands for MEMory EXtender.

[126] Linda C. Smith, "Memex as an Image of Potentiality Revisited," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, eds. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 261.

[127] Zachary, *Endless Frontier*, 265.

[128] James M. Nyce and Paul Kahn, "A Machine for the Mind: Vannevar Bush's Memex," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, eds. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 42-43.

[129] The word Vocorder is adapted from an acronym for an electronic human voice synthesizer created by AT&T for the 1939 New York World's Fair. The device was called Pedro the Vodor (Voice Operation DemonstratOR). See, Nyce and Kahn, "A Machine for the Mind," 44.

[130] Vannevar Bush, "As We May Think," in *From Memex to Hypertext: Vannevar Bush and the Mind's Machine*, eds. James M. Nyce and Paul Kahn (New York: Academic Press, 1991), 87, 93-96, and 102.

including J. C. R. Licklider, Theodor Nelson, and Douglas Engelbert, found inspiration in Memex. These men imagined interacting with computers the way Bush intended to use Memex. Information-processing technologies have indeed come to resemble those Bush described. As a more esoteric feature, Memex allowed building a "mesh of associative trails" that did not "fade" through stored and linked information. That concept is attributed as a rough roadmap to hypertext.[131]

Memex called for digital circuitry but consisted mainly of analog technologies. However, Bush initiated yet another project that probably constituted the first attempt to build a limitedly general-purpose electronic digital computer.[132] Like Atanasoff's, Bush's thinking on digital computation originated mid-1930s with consideration of EAM equipment. Instead of an attachment to expand its capabilities, Bush attempted to harmonize multiple machines with a master controller like Wallace Eckert's.[133] He graduated to the idea of a "highly versatile and amply rapid" computer whose operation was to "depend primarily upon summation of (electronic) pulses." The integrated device would take "its information from previously prepared tapes, to perform the four operations of arithmetic as well as storage of partial results, extraction from storage for further manipulation, and printing of final results."[134] Bush thought enough of the Rapid Arithmetical Computing Machine, or Arithmetical Machine for short, that he intended it to be the lead project for the Center of Analysis after the Rockefeller Analyzer.[135]

The war intervened before that could happen. Nonetheless, much effort went into perfecting vacuum tube counting circuits with funding from NCR. Design engineers anticipated working speeds

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[131] Bush, "As We May Think," 103-105; Zachary, *Endless Frontier*, 398-399. For a good account of the work of J. C. R. Licklider, Theodor Nelson, and Douglas Engelbert, see Campbell-Kelly and Aspray, *Computer*.
[132] Randell, *The Origins of Digital Computers*, 294-295.
[133] Vannevar Bush, "Instrumental Analysis," *Bulletin of the American Mathematical Society* 42 (1936), 654.
[134] V. Bush, "Arithmetical Machine," 1940; reprinted in *The Origins of Digital Computers: Selected Papers*, ed. Brian Randell. 3rd ed. (New York: Springer-Verlag, 1982), 337 and 343.
[135] V. Bush, Dean of Engineering, MIT, copy of letter to Colonel E. A. Deeds, 19 May 1938, 3. Charles Babbage Institute, Honeywell Collection (box 1, folder 8).

of 100,000 or 150,000 pulses per second, but with 10,000 thought more likely.[136] Moreover, the engineers considered switching circuits and magnetic storage devices, particularly steel tape.[137]

Despite strides made, few tangible results came from the Arithmetical Machine. Bush refused any credit for helping invent the modern computer, in fact. In his autobiography, he declared unequivocally: "Who invented the digital computer? I can write at once that I did not, in fact I had little to do with that whole development."[138] This denigration of his role was unfair. Computer historian Brian Randell speculated that Bush downplayed his contributions either because the Arithmetical Machine came to nothing, or because as far as he knew, it did not influence the ENIAC.[139]

Among the reasons MIT did not progress further in digital computing prewar was that the Rockefeller Analyzer took longer than expected, and then the Arithmetical Machine was set aside with onset of war, like the ABC.[140] Project engineers developed computing circuits but had not decided on an overall architecture before the chief engineer, W. P. Overbeck, left in 1942 to help with the atomic bomb. Caldwell had already followed Bush to the NDRC, where he served under Weaver. Moreover, the Center of Analysis had to give full effort to calculating ballistics tables.[141]

Another reason MIT did not make greater progress was that Bush developed other priorities. He remained committed to the Arithmetical Machine as late as March 1940.[142] By then, he had the much weightier issue of organizing research for national defense on his mind. In June, he proposed the NDRC and became its chairman. As such, he assumed responsibility for the great share of research in the United States. Urgent as the situation was, he emphasized short-term projects. The question that guided his selections was, "Will it help win the war; this war?" The digital computer, Bush believed, required long-term effort.[143]

Coincidentally, Atanasoff introduced himself in April 1940 at the Carnegie Institution specifically to attempt to interest Bush in the ABC. Bush received him cordially but showed little

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[136] W. H. Radford, "Brief Report of Progress in the Preliminary Study and Development of the Rapid Arithmetic Machine," unpublished report, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1939, 2 and 4. Charles Babbage Institute, Honeywell Collection.
[137] W. H. Radford, "Report on an Investigation of the Practicality of Developing a Rapid Computing Machine," unpublished report, Massachusetts Institute of Technology, Cambridge, Massachusetts, 15 October 1939, 3. Charles Babbage Institute, Honeywell Collection.
[138] Vannevar Bush, *Pieces of the Action* (New York: William Morrow and Company, 1970), 185.
[139] Randell, *The Origins of Digital Computers*, 295.
[140] Bush, "Arithmetical Machine," 337; Owens, "Vannevar Bush," 19.
[141] Wildes and Lindgren, *A Century of Electrical Engineering and Computer Science at MIT*, 231.
[142] As evident by Bush's attitude expressed in "Arithmetical Machine."
[143] Vannevar Bush quoted in Zachary, *Endless Frontier*, 131; also, 95-102, 112-114, and 266.

interest. Atanasoff decided he had concern only for differential analyzers.[144] That was not true; the NDRC did sponsor further development of electronic counters by NCR but not a full computer.[145]

As a matter of fact, several months after meeting Atanasoff, Bush also refused to fund a computer that Norbert Wiener proposed.[146] Wiener, a mathematician associated with Bush at MIT, wanted to build an advanced digital computer. Writing after the war, he did not mention the Arithmetical Machine but recalled: "These notions were all very much in the spirit of the thought of the time." Among the notions, his computer was to be binary and have flexible programming. Recognizing that an effective computer needed copious fast-acting memory, Wiener apparently considered cathode ray tubes.

Wiener, like Atanasoff, was one of the few prewar mathematicians interested in applications and explained his desire for a digital computer as the need for solving partial differential equations. Too, he thought a sophisticated computer might prove useful if war came. However, Wiener, like Atanasoff, became involved with antiaircraft guns and had to abandon computers.[147]

Bush's change of priorities helps explain why America did little on computers during the war before the ENIAC, which the Army built with money outside of his control. He cannot be blamed for failing to give urgency to electronic digital computers when no one else did either at the beginning of the war. The military did not yet give high priority to new methods for calculating ballistics tables. Code breaking furnished a critical need, but Bush thought his Comparator best for that.

Unacknowledged by historians, intervention by government had serious negative consequences for private research, including that into computing. IBM converted some of its factories to build war materials. It also curtailed research. Patents issued to IBM plummeted from eighty-seven in 1940 to twenty-five in 1946. Moreover, to ensure full retention of employees after what it hoped might be a short war, IBM decided in 1943 to give priority to developing products to go to market quickly. That admirable policy further delayed work in electronic circuits begun before the war. IBM tried to reactivate electronics research later but found all experts committed to defense.

Other office machine manufacturers were in similar straits, and their patents dropped precipitously as well. NCR, where design of electronic calculators had also started before the war

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[144] Atanasoff, interview with Kaplan, 23 August 1972, 111; Atanasoff, interview with Halladay, et al., 10 July 1968, 49-50, and 11 July 1968, 16. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folders 5 and 4).
[145] Joseph R. Desch, "Research Progress Report #1: Electronic Accumulator Research for National Defense Research Committee," 27 January 1941. Charles Babbage Institute, Honeywell Collection.
[146] Zachary, *Endless Frontier*, 265-266.
[147] Norbert Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine* (New York: John Wiley & Sons, 1948), 9-11; *Honeywell*, "Transcript of Proceedings," 2,115.

and which sponsored similar work at MIT, had its production of cash registers totally disrupted. It switched its factories to cryptoanalysis devices and other war-related projects.[148] NCR did wartime research on electronic computing circuits but did not move into commercial computers until the mid-1950s to concentrate on restoring its core business.[149] Of course, Atanasoff and Berry, whose computer had greatest potential, were almost completely sidetracked by the war.

However, despite Bush's opinion, his work at MIT did influence electronic digital computers. Much of that impact was indirect through his and Caldwell's students, including Perry Crawford and, especially, Claude Shannon. Shannon operated the Differential Analyzer as a graduate student in electrical engineering at MIT. He also assisted with the Rapid Selector. His Master's thesis (1937) must rank among the most important ever by describing how Boolean algebra could be used to design efficient switching circuits to mimic logical reasoning. George Boole was a nineteenth-century Englishman who devised an algebra based entirely on binary numbers and three essential operations: *and*, *or*, and *not*. Boolean algebra is perfect for working out many logical operations of digital computers.[150]

Thornton Fry hired Shannon to apply his ideas. Telephone switching furnished a natural application, but Fry also had interest in computers. Urged by Fry, George Stibitz and Samuel B. Williams began building computers at the BTL in 1939. First came the Complex Number Computer, a binary-coded decimal calculator. Complex numbers are arranged in a two-part convention convenient for representing phase and amplitude of electrical signals and require slightly different rules of arithmetic manipulation.

Public demonstration of the Complex Number Computer at a September 1940 conference at Dartmouth was a milestone in information processing because of its remote operation by teletypewriter. According to historian Paul Ceruzzi, the demonstration initiated telecommunications; that is, transport of digital signals over telephone lines. Von Neumann, Mauchly, and Wiener witnessed the event. Mauchly, in particular, took interest in the computer and within a couple of months recorded his intention of building his own electronic calculator.[151]

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[148] Cortada, *Before the Computer*, 210-215 and 219. The figures are from "Table 15.6: Number of Patents Issued, 1940-1946." See also, Pugh, *Building IBM*, 117-122 and 325: "Appendix C: Early Electronic Computing Circuit Patents."

[149] Flamm, *Creating the Computer*, 31, 39-40, and 118-119.

[150] Goldstine, *The Computer from Pascal to von Neumann*, 35-38 and 119-120.

[151] John W. Mauchly, "Mauchly: Unpublished Remarks," *Annals of the History of Computing* 4, no. 3 (July 1982), 246. In the same article, see John W. Mauchly, "letter to H. Helm Clayton, November 15, 1940," 248.

Stibitz left with Fry to work for Weaver at the NDRC, but he initiated the design of six other computers based on work started before the war. The computers were built by the BTL during and shortly after the war. All were relay machines, but several were general purpose and programmable. Most were for the military.[152] As for Shannon, he got placed into related antiaircraft fire control work, like Atanasoff and Wiener.[153]

With its few relay computers, however, the BTL pioneered important concepts. One computer, the general-purpose Model V, set a standard for reliability and versatility. Using about 9,000 relays, it had a more balanced design and greater problem-solving capabilities than the ENIAC. Furthermore, design redundancy meant errors rarely, if ever, occurred due to internal malfunctions. Historians have assumed the Model V was slower than the ENIAC, but relative speeds of the two machines probably varied by situation.[154] Despite the BTL's impressive achievements, antitrust actions by the federal government prevented it from producing commercial computers.[155]

Returning again to Bush, he also had direct influence on the ENIAC through Mauchly. Mauchly may or may not have known about developments in digital technology at MIT, but he became well acquainted with differential analyzers. In a nutshell, the ENIAC mated the architecture of a differential analyzer with the computational design of a tabulator, which explains why it became such a cumbersome machine.

The ancestry of the ENIAC provides a key to understanding Bush's reluctance to continue research wholeheartedly into digital computers under auspices of the NDRC. After he reviewed the ENIAC proposal, Caldwell recalled that a similar project had been rejected at MIT.[156] Bush and his group certainly would have considered a computer whose main elements consisted of electronic accumulators incorporated into the architectural framework of a differential analyzer. The Rockefeller Analyzer represented a big step in that direction. Strong circumstantial evidence therefore suggests that Bush saw the Arithmetical Machine as becoming overly complex, like the ENIAC. Difficulties with the Rockefeller Analyzer could only have reinforced his skepticism. After

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[152] Ceruzzi, *The Reckoners*, 73-101; Randell, *The Origins of Digital Computers*, 242-244.
[153] Robert Slater, *Portraits in Silicon* (Cambridge, Massachusetts: MIT Press, 1987), 34-36; Nyce and Kahn, "A Machine for the Mind," 40.
[154] Frank L. Alt, "A Bell Telephone Laboratories' Computing Machines," 1948; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 263-265, 269, 284, 289, and 291-292.
[155] However, the BTL built the TRADIC, the first completely transistorized computer, and various other computers and related equipment, both for itself and for the military. Flamm, *Creating the Computer*, 119-122.
[156] SHC (Samuel H. Caldwell), memorandum to HLH (Harold L. Hazen), 23 October 1943. University of Pennsylvania.

Bush left MIT, however, Overbeck simplified the Arithmetical Machine's circuitry, particularly with novel vacuum tubes.[157] For his part, Caldwell remained optimistic, even if not impressed by the ENIAC. Historians of the Arithmetical Machine believe that, had war not intervened, a simplified version would have resulted by 1945.[158]

After talking to Caldwell in 1941, it also occurred to Atanasoff how the ABC and a differential analyzer could be crossed to solve integral equations. He did not have the opportunity to go further but discussed his idea with Mauchly.[159] Unfortunately, Eckert and Mauchly did not grasp the unorthodox beauty and simple elegance of the ABC as a superior basis on which to build. They failed to see that not only had Atanasoff and Berry pioneered a more efficient method of performing calculations, but also pointed the way to effective memories, without which great computational speed means little. Lacking the experience of Bush and Caldwell to comprehend the inherent limitations of accumulators, Eckert and Mauchly regressed to the model of the old technology. Caldwell's judgment of the ABC to be viable, but not the ENIAC, proved correct.

The usual explanation for Bush's failure to continue development of digital computers is that he was too tied to analog, as Atanasoff suspected. There may have been truth to that, because analog computers had advantages. It took years before digital emerged as clearly superior. For example, eight years after startup of the ENIAC, one authority, voicing a still prevalent view, acknowledged that digital computers might have more potential but otherwise saw no absolute advantage. Digital computers had greater flexibility but tended to be bulkier. Moreover, while digital computers operated very fast, that did not mean faster completions of applications. For one thing, data input and output were usually easier in analog.[160] As a bonus, some analog devices, such as the Laplaciometer or differential analyzer, allowed those not proficient in mathematics to "see" the unfolding of the solution to a problem. Thus, analog computers and hybrid digital differential analyzers continued to be built and used long after the ENIAC supposedly marked the end of such machines.[161]

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[157] For example, Overbeck developed a vacuum tube with ten elements to replace ten ordinary tubes. Bush, "Arithmetical Machine," 339.

[158] Wildes and Lindgren, *A Century of Electrical Engineering and Computer Science at MIT*, 229-235. See in particular, quotations from a letter from Caldwell to Warren Weaver, 232.

[159] J. V. Atanasoff, copy of letter to J. W. Mauchly, 31 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14); Atanasoff, interview with Merzbach, 5 May 1969, 80-82 (actually unnumbered).

[160] Morris Rubinoff, "Analogue vs. Digital—A Comparison," *Proceedings of the I.R.E.* 41, no. 10 (October 1953), 1,261-1,262.

[161] See for example, Max Palevsky, "The Design of the Bendix Digital Differential Analyzer," *Proceedings of the I.R.E.* 41, no. 10 (October 1953), 1352.

The deciding factor for Atanasoff was that only a digital computer could give the accuracy he needed. A digital computer becomes more accurate by expanding word size. By contrast, the precision of its mechanical components, including slippage and backlash, limited the accuracy of a differential analyzer and was normally less than that easily obtainable in a digital computer. Moreover, an analyzer lost accuracy as it wore. Wear is seldom a problem in a digital computer, which tends to work or not.

In summary, it was the 1920s before there began to be much interest in using calculators for large computations. Interest coincided with the maturing of the devices but stemmed from a new appreciation for applied mathematics. Researchers concerned with statistical analysis led the way, pushed by proponents like Wallace and Snedecor. Astronomers and physicists followed, with Comrie and Hylleraas at forefront. Meanwhile, Bush, an engineer, began building the analog Differential Analyzer for solving electrical circuit equations. It was the most powerful calculator of the time but had less accuracy than the common digital machines. Accuracy was not so important in engineering applications, typically including safety factors. Moreover, the Analyzer did not rely upon numerical methods, still unsuited for extensive computations.

Use of EAM equipment for information handling expanded in the 1930s, but desire for calculating power grew more. Development of electromechanical digital computers thus began. Bush conceived of electronic digital computers but devoted more effort to the Rockefeller Analyzer and futuristic information-processing machines like the Rapid Selector and Memex. Atanasoff and Berry built the ABC.

The years before World War II therefore yielded a wealth of computer-related theory and technologies, including some not yet discussed. Scientists got such credit as has been given, but the office appliances formed the foundation of their efforts. Furthermore, imperious demands for improvements in information handling drove the office appliance industry forward as well. The ABC departed from the technology of the day and established the future direction for computers, but Atanasoff recognized its lineage. When preparing a patent application, he stipulated no "line of demarcation" between the ABC as "Scientific Machine" and EAM equipment.[162]

The incremental nature of business dictated caution in commercial machines, but the office appliance industry was nonetheless quite creative. It boldly explored new technologies on its own

[162] Richard Trexler (attributed), Patent Attorney for Cox, Moore & Olson, copy of proposal for J. V. Atanasoff, 19 December 1940, 2. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

and generously supported projects by outside inventors. It is not exaggerating too much to say that the history of IBM, directly and by association, is the history of computers, even if only a portion of related innovations originated within the company. That history begins with the tabulating equipment of Hollerith. It includes pioneering work in scientific applications at Columbia University. It includes the ASCC and missed opportunity with Atanasoff. It includes the SSEC, perhaps the first stored-program computer. IBM has since routinely built cutting-edge machines. A recent example is a computer nicknamed Blue Gene, which if completed satisfactorily on schedule in 2005 will have outpaced computing-power growth predicted by Moore's Law by a factor of three. Blue Gene will cost $100 million and operate at more than one quadrillion operations per second, making it the fastest computer ever.[163] Otherwise, IBM continues as an innovation champion. In 1999, it received an astonishing 2,756 U.S. patents, more than any other entity. Meanwhile, IBM (including predecessors) has been the most successful vendor of computing equipment for most of its history, employing the same skills in mass manufacturing and sales of computers that it applied to EAM equipment. Even so, other firms created and garnered much of the business in personal computers, as Microsoft did for software.

Government, too, has long been involved with the information-handling industry, but largely limited its role to customer and regulator until World War II. More was probably not needed. The private sector's interest in the ABC proved it was receptive to the electronic digital computer at its inception. The extent of its enthusiasm was demonstrated by its funding of expensive machines like the ASCC and Rockefeller Analyzer, among numerous other related projects, even in the Depression. The ABC suggests modest investments were sufficient. More generally, the successes of the private sector developing technology and science before the war suggests that government backing was not critical to either afterwards.

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[163] IBM Press Release, "IBM Unveils $100 Million Research Initiative to Build World's Fastest Supercomputer," 6 December 1999.

CHAPTER 4. IN THE BEGINNING, THE ABC

Atanasoff despaired by late 1937. He maintained a full load of teaching and research. Plus, he supervised a number of graduate students. He did not want to investigate computing technologies as an aside to all that, but believed he had little choice. Most research he or his students undertook involved partial differential equations that they transformed by necessity into linear algebraic equations. To obtain the solution accuracy desired, however, generally required large sets of equations unsolvable with ordinary calculators, much less by hand. Furthermore, Atanasoff found even the most advanced computing mechanisms inadequate and recently had rejected ideas for devising a more powerful but simple calculator, either with a tabulator and attachment or by ganging desktop machines. For his students to progress in their research, he therefore faced attempting to create a new type of computing machine from first principles. Yet, his efforts in that direction had also come to naught, other than he resolved that his computer had to be digital for sake of accuracy and economical to build and operate.

He was not then even sure if a computer should be mechanical or electrical. He sensed that a digital computer might exhibit better stability made from mechanical components, but his education and experience inclined him toward electrical or electronic.[1] As one advantage, electronic elements do not have frictional and inertial limitations that inhibit mechanical devices.[2] Electromechanical mechanisms of various sorts were common, of course, but so were electronic ones. In fact, Atanasoff built electronic counters using technology then current. He had not been able to make them perform consistently enough for a high-capacity calculator, however. This failure, too, weighed heavily upon him.

Like many things electrical, electronics began with Thomas Edison. The prolific inventor found in 1883 that placing a positively charged metal plate near the carbon filament in an evacuated incandescent light bulb incited current to flow from the filament to the plate. The phenomenon became known as the Edison effect and was his sole scientific discovery. He did nothing with it, however, probably because of his preoccupation with lighting systems.

John Ambrose Fleming consulted with Edison and learned of the Edison effect. Years later,

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[1] John Vincent Atanasoff, "Advent of Electronic Digital Computing," *Annals of the History of Computing* 6, no. 3 (July 1984), 237.

[2] J. V. Atanasoff, New Market, Maryland, interview with B. Kaplan, 23 August 1972, 100-101. Smithsonian.

he used it to create the two-element vacuum tube, or diode. A diode is a circuit device characterized by low resistance in one direction and high resistance in the other. Current flows easily against the low resistance but is effectively blocked in the opposite direction. The consequence was that a vacuum diode acted as a rectifier; that is, input of an alternating current produced a unidirectional current output. An early application was demodulation of radio signals.

Two years after Fleming invented the vacuum tube diode in 1904, Lee de Forest added a wire mesh grid between the two elements to create the three-element vacuum tube, or triode. A positive voltage applied at the grid caused current to flow from the negative cathode to the positive anode, or plate. The triode thus acted like a diode with an on-off switch. However, the current that flowed through the triode varied with grid voltage. As the grid became slightly positive relative to the cathode, current began flowing. As the grid became more positively charged, proportionally greater amounts of current flowed until the triode behaved roughly like a fixed resister.[3] As a consequence, triodes could amplify the current or voltage applied at the grid. That is, a small voltage at the grid allowed control of a relatively large current between the cathode and anode. However, the first triodes had little amplification capabilities. Triodes became important in 1912 when Edwin Howard Armstrong and others working independently connected the plate to the grid so that a portion of the plate voltage simultaneously appeared at the grid. The result was the positive feedback, or regeneration, circuit. Furthermore, they discovered that with enough feedback an amplifier became an oscillator that produced constant frequency sine waves useful for single-channel radio transmission, among other things.

Electronics matured by World War II, but historians regard the conflict as its turning point. One reason is that the value of electronics hardware manufactured in the United States increased by more than twelve times during the war. Even so, the war continued the long-term trend, because growth of the industry had been accelerating since the invention of the triode oscillator, thanks largely to telephone and radio.[4] More telling, the pace of the war years did not match that of the Depression when measured by innovation, contrary to the assertion that government-sponsored research produced a proportional rise in new technologies.[5] Of twelve or so circuits considered basic and from which all others derive, for example, most were invented by 1940, including the phase-locked loop, automatic

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[3] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W. W. Norton, 1997), 58.

[4] Editors of *Electronics, An Age of Innovation: The World of Electronics 1930-2000* (McGraw-Hill, 1981), 12, 44, and 178.

[5] See for example, W. C. White, "Evolution of Electronics," *Electronics* 25, no. 9 (September 1952), 98.

frequency control, noise blanker, and operational amplifier in the 1930s alone. On the other hand, no fundamental circuit can be attributed to the war. Probably the greatest contribution of war-related electronics research was in circuit miniaturization, especially for proximity fuses, but miniaturization represented the inevitable long-range trend, war or no war.

As another example of the fruits of prewar privately funded research, most categories of vacuum tubes were on the market by 1930. Available types of tubes doubled to three hundred between 1931 and 1932 alone. New uses for tubes evolved continually, including heavy-duty industrial applications previously performed by relays. Military equipment contained some 2,300 types of vacuum tubes by the war and made standardization a major concern.[6]

Many sophisticated electronic devices made appearances during the Depression. These ranged from the fluorescent lamp to the commercial electron microscope and cyclotron, to name several.[7] The cathode ray tube can be traced to the late nineteenth century, and by 1940 the electron beam device had evolved into the oscilloscope. Among other things, it also became television. Some attribute television to Philo Farnsworth, an Idaho farm boy who when fourteen conceived of television while cutting hay. Without formal training, he was awarded over 150 related patents. Other inventers included Vladimir K. Zworykin, who invented a kinescope (picture tube) in 1933 and iconoscope (camera tube) in 1938. His employer, RCA, began regular television broadcasts from the Empire State Building in 1939. Furthermore, although usable transistors did not appear until the late 1940s, research into solid-state devices began much earlier, largely as an outgrowth of research into crystal physics and vacuum tubes. Various inventors began considering transistor prototypes by 1925. Solid-state diodes from copper oxide were produced in large numbers before and during the war, but much related research stopped for the duration.[8]

Most of the impressive and numerous innovations in electronics resulted from capitalism in action, even in the dark days of the Depression, and not from government programs. Wartime developments, such as they were, also depended heavily on privately funded work. The electronic digital computer shares that genesis. That so much new technology has been attributed to the war is largely explained by the need to justify unprecedented amounts of money spent by government on research and the desire by many to have the funding continue, particularly to compete with the USSR in the Cold War.

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[6] Editors of *Electronics, An Age of Innovation*, 9, 12, 26, 44, and 178-184.
[7] White, "Evolution of Electronics," 98.
[8] Editors of *Electronics, An Age of Innovation*, 17, 27-29, and 66-71.

Vacuum tubes through World War II were almost exclusively used in analog services, particularly in amplifying and oscillation circuits. Electronic digital circuits existed, however. W. H. Eccles and F. W. Jordan co-invented the first electronic digital circuit in 1919.[9] It consisted of two triodes interconnected so that the plate of each fed the grid of the other, resulting in only one tube conducting at a time.[10] Eccles and Jordan called their invention a trigger relay, because the two tubes reversed states when triggered by an outside pulse. The formerly conducting tube became non-conducting and vice versa. That is, the states of the tubes flip-flopped when triggered, and for that reason such circuits popularly came to be called flip-flops. The flip-flop and related circuits were inherently binary memory devices but could be chained together in stages to form counters, something like an odometer. In the early 1930s, C. E. Wynn-Williams began constructing "scale of two" counters from flip-flops for experiments in physics.[11] Cosmic ray counters using such counters received much attention in the 1930s.[12]

Of numerous efforts to construct electronic computing circuits before the war, most involved variations of flip-flop counters. A main impediment to the electronic digital computer was not so much creating an effective counter, as how to incorporate the devices into a machine of reasonable size and complexity. With the deep pockets of the U.S. Army opened for them, Eckert and Mauchly ignored those concerns and in the ENIAC produced a computer with limited capabilities or technological influence and no commercial value.

Eckert perfected a decade counter from ten flip-flops as the essential element of the ENIAC. The counter needed ten flip-flops because the ENIAC computed with decimal numbers. Each flip-flop in the decade counter represented a decimal digit, one through ten, and only one flip-flop of the ten was "set " (in the active position) at any time. Each new pulse advanced the counter one stage by disengaging the active flip-flop and setting the next. The ENIAC had twenty accumulators that performed arithmetic and served as memory, and each accumulator contained ten such decade

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[9] W. H. Eccles and F. W. Jordan, "A Trigger Relay Utilising Three-Electrode Thermionic Vacuum Tubes," *The Radio Review* 1 (December 1919), 143-146.

[10] Arthur W. Burks, "Electronic Computing Circuits of the ENIAC," *Proceedings of the I.R.E.* 35, no. 8 (August 1947), 758.

[11] C. E. Wynn-Williams, "A Thyratron 'Scale of Two' Automatic Counter," *Proceedings of the Royal Society of London, Series A*, 136 (June 1932), 312-324.

[12] Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 293.

counters.[13] That gave the ENIAC its read-write memory capacity of twenty ten-digit numbers.

Atanasoff experimented with scale-of-two counters through the last months of 1937. He got them to work but not reliably enough for a computer. Why the counters did not function better is unclear, but may lie in his application rather than the counters. Eckert and Mauchly deliberately patterned the accumulators of the ENIAC on a mechanical calculator. That is, an ENIAC accumulator functioned electronically like the common calculators did mechanically. Atanasoff considered mimicking mechanical calculators but wanted greater capabilities.[14] Foremost among those, he recognized need for a larger memory. He therefore separated the memory from the arithmetic unit, permitting not only a memory of greater capacity but also overall flexibility. For example, a distinct memory could easily be structured as multiple memories, hierarchically arranged.[15] Moreover, where mechanical calculators and the ENIAC acted on digits in parallel, Atanasoff chose sequential transfer of digits from the memory to the arithmetic unit.

Sequential calculation with digits, Arthur Burks believed, may have been the source of difficulties that Atanasoff encountered with scale-of-two counters. Burks received a doctorate in philosophy before going to the University of Pennsylvania as an instructor of electrical engineering. He then became a principal designer of the ENIAC. In fact, he first heard of Atanasoff while assisting Eckert and Mauchly but thought little of it. Years later, Burks investigated the ABC after his interest became piqued by the Honeywell trial. Despite loyalty to the ENIAC and initial skepticism, he found that the ABC was indeed the first electronic digital computer. With his wife, Alice, Burks published *The First Electronic Computer*, providing a detailed description of the ABC and its operation. Based on his study of the ABC and long experience, Burks concluded that scale-of-two counters simply did not lend themselves to the use Atanasoff attempted to make of them.[16]

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13 Burks, "Electronic Computing Circuits of the ENIAC," 757-759 and 763; Arthur W. Burks, "Super Electronic Computing Machine," *Electronic Industries* (July 1946), 64; Arthur W. Burks, and Alice R. Burks, "The ENIAC: First General-Purpose Electronic Computer," *Annals of the History of Computing* 3, no. 4 (October 1981), 348-349.

14 Atanasoff, "Advent of Electronic Digital Computing," 239; John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 24 April 1972, 21-24. Smithsonian.

15 John V. Atanasoff, transcript of interview with Bonnie Kaplan, Smithsonian Institution, 10 August 1972, 3. Smithsonian.

16 Alice R. Burks and Arthur W. Burks, *The First Electronic Computer: The Atanasoff Story* (Ann Arbor, Michigan: University of Michigan Press, 1988), v-vi and 18-19.

Incidentally, flip-flops are another of the fundamental electronic circuits and continue to be important. They are still used in computers, in fact, particularly as fast-acting elements in registers.[17]

Development of a reliable electronic digital counter was but one of the fundamental computer-related problems Atanasoff faced in late 1937. He also could not decide on a number base. Computing with binary, or base-2, numbers seems natural today, but that is because binary numbers match perfectly with digital circuitry and combinational logic. Before Atanasoff and others introduced those concepts, decimal, or base-10, numbers had overwhelming appeal. All the desktop calculators and EAM machines used decimal numbers. Decimal digital computers continued to be built through the 1950s, particularly for accounting applications, but also including the LARC supercomputer completed by Sperry Rand in 1960.[18] Atanasoff defined many basic characteristics of electronic digital computing, including internal binary operations. Even so, concepts inherent to the ABC became universal only after considerable subsequent debate and experimentation.

Mathematician that he was, Atanasoff recognized advantages to bases besides decimal or even binary. He understood that the selection of a base involved compromises. Higher bases offered compactness; that is, need for fewer digits to represent numbers, and Atanasoff considered bases to one hundred. On the other hand, lower bases stood out for ease of arithmetic operations. Atanasoff calculated that *e*, the natural base equal to approximately 2.7183, should permit fastest computations, but of course, a computer number base should be an integer.[19] Atanasoff studied the matter at length before deciding that binary was best overall, allowing over 37 percent greater efficiency than decimal.[20] Even so, he expected resistance if he selected anything but decimal.[21]

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[17] Editors of *Electronics*, *An Age of Innovation*, 178-179; David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware / Software Interface* (San Francisco: Morgan Kaufmann, 1994), B21-B24.

[18] LARC is an acronym for Livermore Automatic Research Computer. Charles J. Bashe, et al., *IBM's Early Computers* (Cambridge, Massachusetts: MIT Press, 1986), 439.

[19] John V. Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," August 1940; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 317-318; Atanasoff, interview with Kaplan, 10 August 1972, 12-16.

[20] Four binary digits are needed to represent the number ten in decimal. However, four binary digits are capable of representing numbers up to the decimal sixteen. Thus, a decimal computer using binary elements wastes six of sixteen possible alternatives. See Norbert Wiener, *I am a Mathematician: The Later Life of a Prodigy* (Garden City, New York: Doubleday, 1956), 236-237.

[21] In fact, Atanasoff continued to consider decimal computers himself. Atanasoff, interview with Kaplan, 10 August 1972, 21-22; Atanasoff, interview with Tropp, 24 April 1972, 11-13.

The issues of number base, memory medium, and whether the computer should be electrical or mechanical had to be considered together. For example, a mechanical computer with a base higher than two might use sliding or rotating memory elements that could be latched into any of a number of positions equal to the base. Alternatively, binary elements could be combined in sets equal to the number base, just as ten flip-flops could be fashioned into a decade counter.[22] As a mechanical binary element, Atanasoff thought of something like a toy spring-loaded clicker that could be toggled from one stable position to the other.[23] As an electromechanical possibility, he considered a "moving reed like the armature of a polarized relay, moved by electromagnetic action." He also thought of vacuum tubes and capacitors.[24]

Actually, magnetic elements had greatest appeal. Atanasoff got the idea from Valdemar Poulsen,[25] a Danish physicist who in 1893 invented the first magnetic storage device, the telegraphone. Its purpose was to record telephone conversations on steel piano wire. The telegraphone worked well, except it produced low volume sound in those days before vacuum-tube amplification.[26] Besides magnetic wire, Clifford Berry recalled that he and Atanasoff had "seriously considered using magnetic drums, but . . . abandoned this approach because of anticipated low signal voltage."[27] Whether magnetic drums, discs, or wire, Atanasoff and Berry decided they could not afford the expense of amplification.[28]

Thus, as things stood in late 1937, Atanasoff had a desperate need for a high-capacity computer and a tangle of ideas "rattling around" in his mind of how such a machine might work, but which had failed to jell into a coherent whole. Things came to a head one day in particular. That afternoon, Atanasoff met with some of his students, including probably Philip Hart and Charles Thorne, to discuss the computational impediments to their work. He went home for dinner and returned to his office determined to make the decisions necessary to build a computer. He sat

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22 Atanasoff, "Advent of Electronic Digital Computing," 237-239.
23 Atanasoff, interview with Tropp, 24 April 1972, 16-17; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Transcript of Proceedings," 1,695. ISU, Parks, "John Vincent Atanasoff Papers" (box 43).
24 Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 318.
25 Atanasoff, "Advent of Electronic Digital Computing," 231 and 258.
26 "Poulsen Telegraphone," *Scientific American* 83, no. 12 (22 September 1900), 181.
27 Clifford E. Berry, copy of letter to R. K. Richards, 12 July 1963. ISU, Parks, "John Vincent Atanasoff Papers " (box 25, folder 23).
28 Atanasoff, interview with Kaplan, 10 August 1972, 27-28 and 37; Atanasoff, interview with Kaplan, 23 August 1972, 63-64; *Honeywell*, "Transcript of Proceedings," 1,733.

nervously at his desk and attempted to harness his mind to the effort but no answers came.[29]

Atanasoff himself best described events as follows:

> Well, I remember that the winter of 1937 was a desperate one for me because I had this problem and I had outlined my objectives but nothing was happening, and as the winter deepened, my despair grew and I have told you about the kind of items that were rattling around in my mind and we come to a day in the middle of winter when I went out to the office intending to spend the evening trying to resolve some of these questions and I was in such a mental state that no resolution was possible. I was just unhappy to an extreme, and at that time I did something that I had done on such occasions, that I used to do on such occasions—I don't do it anymore—I went out to my automobile, got in and started driving over the good highways of Iowa at a high rate of speed.
>
> I remember the pavement was clean and dry, and I was forced to give attention to my driving, and as a consequence of that, I was less nervous, and I drove that way for several hours. Then I sort of became aware of my surroundings. I had, of course, been aware of the road before, but then I became aware of where I was and I had reached the Mississippi River, starting from Ames and was crossing the Mississippi River into Illinois at a place where there are three cities, one of which is Rock Island.
>
> I drove into Illinois and turned off the good highway into a little road, and went into a roadhouse there which had bright lights. It was extremely cold and I took off my overcoat. I had a very heavy coat, and hung it up, and sat down and ordered a drink, and as the delivery of the drink was made, I realized that I was no longer so nervous and my thoughts turned again to computing machines.
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> Now, I don't know why my mind worked then when it had not worked previously, but things seemed to be good and cool and quiet. There were not many people in the tavern, and the waitress didn't bother me particularly with repetitious offers of drinks. I would suspect that I drank two drinks perhaps, and then I realized that thoughts were coming good and I had some positive results.
>
> During this evening in the tavern, I generated within my mind the possibility of the regenerative memory. I called it 'jogging' at that time. I'm thinking about the condensers for memory units, and the fact that the condensers would regenerate their own state, so their state would not change with time. If they were in the plus state, for instance, they would stay in the plus state; or, if they were in the negative state, they would stay in the negative state. They would not blink off to zero. Or if you used two positive charges, they would retain their individual identity and would not leak across to each other.
>
> During the same evening, I gained an initial concept of what is called today the 'logic circuits.' That is a non-ratcheting approach to the interaction between two memory units, or, as I called them in those days, 'abaci' . . . I visualized a black box at that time but not the inner workings. There would be a black box, and a state of abacus 1 would pass into the box and the state of abacus 2 would pass into the box, and the box would then yield the correct results on output terminals. And sometime late in the evening I got in my car and drove home at a slower rate.[30]

Atanasoff retold this story many times of how the ideas for the ABC came together while he

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[29] John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 1 May 1972, 75-76. Smithsonian.

[30] *Honeywell*, "Transcript of Proceedings," 1,700-1,703.

sat in a roadhouse in Illinois and nursed a drink, or "maybe two," of bourbon and soda one bitter cold winter evening.[31] A couple of notes are in order. First, Atanasoff was an unusually aggressive driver and Iowa had no speed limit. Partial to V-8 Fords (also preferred by gangster John Dillinger for making a quick getaway), Atanasoff loved to drive fast while whipping in and out of traffic to pass. He found it therapeutic.[32] In the days before seatbelts, all passengers could do, including his children being raced across town to school, was spread their legs to brace themselves and to hang on for dear life.[33] One hapless passenger recalled Atanasoff telling him that he liked to drive so fast that if he took his mind off the road for a moment he would die. They were barreling down the highway at breakneck speed at the time.[34] The point is that his mode of driving to Illinois, in which he traveled east an estimated 189 miles at night over a two-lane highway and through numerous towns in less than three hours, was not unusual.[35] Second, as to when he returned home, Atanasoff recalled that it was "well towards daylight, if not daylight, when I got back. I spent the night at it."[36] That, too, was not exceptional. He often spent the night, or its better part, working.

To reiterate what Atanasoff accomplished in the roadhouse, he made four decisions difficult to overestimate in importance. First, his computer would be electronic. Second, internal arithmetic would be conducted with binary numbers. Third, he decided to use capacitors, which he called condensers, as memory elements. Capacitors had the advantage that signals from them could be fed directly into vacuum tubes without intermediate amplification. However, a capacitor looses its charge in a few minutes or less, so it needs frequent recharging. Atanasoff used the term jogging for recharging, also called regeneration or refreshing. Thus, he decided to retain data in memory through periodic jogging.

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[31] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 9 July 1968, 17. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 5).

[32] Atanasoff, interview with Tropp, 1 May 1972, 75-76; *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Dr. John V. Atanasoff," 1,073. ISU, Parks, "John Vincent Atanasoff Papers" (box 31, folder 1).

[33] Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone with Paul Mobley, 1 July 1998.

[34] Robert M. Stewart, Ames, Iowa, tape-recorded interview with Paul Mobley, 14 November 1997.

[35] Atanasoff, interview with Halladay, et al., 9 July 1968, 18 and 25.

[36] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 1,072.

Finally, and most nebulously, the computer would operate by "direct logical action."[37] Exactly how logical action might work, Atanasoff did not know.[38] He simply imagined a logic circuit as a "black box," with details to be formulated later.[39] More fundamentally, he imagined the black box as a human brain: "it is a black box into which go various sensory signals and which is capable of remembering previous sensory signals. Out of this black box came conclusions derived from the signals, both present and past."[40] He had considerable flexibility in design of the black box, since he had separated the arithmetic unit from the memory. Moreover, he could forget scale-of-two counters, because he now envisioned a superior method of computing.

Scientists speak of "eureka" moments of penetrating insight, and no doubt Atanasoff had one that night. However, during a deposition he corrected a lawyer who commented on his "flash of genius." It was no such thing, Atanasoff admonished and continued: "I don't really much believe in genius. I believe in ditch digging and a lot of hard work."[41] His point was that, although the concepts for the ABC came together in the bar, he had actually been mulling them over separately for a long time. Reflecting back on the decisions years later, he elaborated: "I do not suppose that the actual decisions were made there (in the roadhouse); they must have been latent in my mind, coming to incisive action there. I now knew how I would get ahead, even though I might change any of the four decisions. In the end, I accepted them all."[42]

Actually, Atanasoff continued to fret over his key decisions for months before finally accepting them. If he had put in years of ditch digging before a coherent structure of a computer at last occurred to him in the tavern, it took months more hard labor in planning before he embarked on construction. Unfortunately, there are few extant records of Atanasoff's computer-related activities between the night in the Illinois tavern and spring 1939, when he first requested funds from ISC to begin the ABC. Atanasoff certainly spent time considering the details of the electronic logic circuits; that is, what was to go into the black box. Preparing for the Honeywell trial, Atanasoff recalled he

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[37] Atanasoff, "Advent of Electronic Digital Computing," 240 and 242.
[38] Nor could Atanasoff say where he had gotten the idea of computation through logical action. Strictly speaking, he did not claim the concept, *per se*, as original to him. Atanasoff, interview with Kaplan, 10 August 1972, 1-4.
[39] John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 11 May 1972, 132-135. Smithsonian.
[40] John Vincent Atanasoff, transcript of interview with Henry Halladay and Charles Call, 20 September 1968, 9. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 7).
[41] *Honeywell*, "Deposition of Dr. John V. Atanasoff," 1,072.
[42] Atanasoff, "Advent of Electronic Digital Computing," 240.

might have been ready to start fabrication sometimes in 1938. Upon inquiring informally about funding, however, he had found none available that year.[43]

In 1940, at the request of Atanasoff, George Gross, a former student, wrote a "resume" as evidence of conception of the ABC.[44] Gross summarized what he knew of ABC-related activities from about 1935, when he first remembered Atanasoff discussing a need for a "linear equation solver." He agreed that most concepts for the ABC had come together by end of 1938, although he could recall no discussion of vacuum tubes in a computing machine until probably 1939.[45]

In any case, in March 1939, Atanasoff formally approached the Iowa State College Council on Research for funding. His letter read as follows:

> Gentlemen:
>
> For the mathematical treatment of many practical problems, one requires the solution of systems of linear simultaneous algebraic equations. As three examples of such problems of continual interest to investigators on our campus, one may mention, (1) Electrical circuit analysis, (2) Approximate solution of the differential equations of mathematical physics with special emphasis on their technological applications, (3) Multiple correlation in statistics. The theory and method of solution of such systems is well known and, if the number of unknowns is small (the number of equations is generally equal to the number of unknowns) the solution presents no difficulty. However, the satisfactory treatment of many problems, the three mentioned above, for instance, frequently requires the use of many unknowns. Since the time of solution of such a system varies roughly as the cube of the number of unknowns the solution of the larger systems becomes extremely arduous.
>
> About six years ago, I started to think about the possibility of mechanizing this solution. After I had succeeded in forming a rough outline of the process necessary, I attempted to realize this process by using the computational capacity of the punched card tabulating equipment. I finally abandoned this attempt because it would require considerable changes in the machines themselves which are leased to the user on a basis that would not permit such changes and because even the large computational capacity of these machines is not high enough. The construction, from the beginning, of a machine to perform necessary functions seemed too involved for successful completion with the means at hand.
>
> However, about two years ago I came to realize that computing machines can be much simplified by changing from the use of numbers to the base 10 to the use of numbers to the base 2. Further study has reinforced this point of view and it now seems possible to build into a small machine of perhaps the size and intricacy of a Monroe a computational capacity over twice that of the 8 bank punched card tabulation. This would be, as far as I am aware, the most powerful computing machine in existence and would furnish a direct and satisfactory method of solving simultaneous linear equations.

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[43] Atanasoff, interview with Halladay, et al., 9 July 1968, 55.

[44] J. V. Atanasoff, copy of letter to George L. Gross, Department of Mathematics, A&M College of Texas, 2 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 9).

[45] George L. Gross, letter to J. V. Atanasoff, 19 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 12).

> While the basic idea of this machine is original. I have made careful calculations and it will work. Therefore. I wish to request a grant of $450 for a research fellow in physics to work on the plan and $200 for materials and mechanical assistance.[46]

This memorandum is helpful in summarizing events to date but less so in understanding subsequent developments. Even Atanasoff could not completely explain what he had meant when asked about the memorandum by lawyers preparing for the Honeywell trial. For instance. it is not clear why he asked for only $650. far too little to build the ABC. More intriguing is how he thought he could create a computer the size of a Monroe. a relatively small desktop calculator. with twice the power of a large tabulator.

Part of the answer is that $650 was the amount of money ISC could provide. not what Atanasoff needed. Furthermore. he may not have been requesting funding for the ABC but for a prototype to prove the underlying concepts. As it happened. he and Berry built a prototype that was a smaller and simpler version of the ABC. Atanasoff originally had in mind a different prototype. however. one to calculate pi to several hundred places. Considerable computational power would have been needed. and Atanasoff recalled that he had planned the pi calculator to be about the size of a Monroe.[47] However. evidence suggests that the Research Council understood the money was for a prototype as built.[48]

Finally. nowhere in the memorandum did Atanasoff mention electronics. Gross may not have been fully aware of Atanasoff's progress.[49] but after his trip to the roadhouse in Illinois. and subsequently abandoning scale-of-two counters. Atanasoff worked out most of the problems of computing with vacuum tubes and logical action. He documented that transition in thinking in a 1940 manuscript as follows:

> The first plans made were to use the circuit of the scale-of-two counters but after months of experimental work this idea was abandoned because of the inherent instability of the circuits. At times these circuits could be made to work but obscure factors strongly influenced their operation. At last the writer hit upon another type of circuit that in the end proved very stable and entirely satisfactory in other ways. This circuit operates upon new principles in the computing art. principles that are rather analogous to the function of the human brain in mental calculation. The circuit takes cognizance of what is in a given abacus (memory) element. what is to be added into or subtracted from the element. and from a memory device it receives a signal indicating carry over from the previous place. Having been taught by a man with a soldering iron it selects the right answer and replaces what is in the counter by

[46] J. V. Atanasoff. memorandum to the Iowa State College Research Council. 24 March 1939. ISU. Parks. "John Vincent Atanasoff Papers" (box 26. folder 4).
[47] Atanasoff. interview with Halladay. et al.. 9 July 1968. 41. 51. 55. and 61.
[48] J. V. Atanasoff. copy of letter to E. W. Lindstrom. Chairman. Council on Research. 9 April 1940. ISU. Parks. "John Vincent Atanasoff Papers" (box 26. folder 4).
[49] Atanasoff. interview with Tropp. 1 May 1972. 86.

> this result. The computing mechanism, being a vacuum-tube circuit, operates at such speed that it can be used over and over again to add the various digits, and additional places only require the use of additional abacus elements, that is, additional condensers. At the same time the over-all complexity and cost of the computing machine is greatly reduced.[50]

This passage reflects Atanasoff's colorful language. For example, when he wrote of a circuit "taught by a man with a soldering iron," he meant that it could be designed and wired to perform particular logical operations. Moreover, the passage further emphasizes that, like von Neumann, Atanasoff thought of the brain as the model for a computer. In fact, Atanasoff and Berry sometimes referred to the main computing modules of the ABC, formally known as add-subtract mechanisms, or ASMs, as "electronic brains." Finally, Atanasoff realized that once he conceived of computing by logical action, he had no further need to consider flip-flop counters because of the advantages of the former for reduction of complexity and costs.

One reason Atanasoff did not use the word electronics may have been that it was not yet common. That is, electronic circuits were not yet recognized as distinct from electrical ones, although his memorandum did not discuss electrical circuits either. Apparently another reason Atanasoff did not mention electronics is that he hoped to avoid detailed discussions. A computer based on scale-of-two counters would have been a bold undertaking, but he had something more radical planned, and even he had doubts that vacuum tubes could add and subtract through switching action. He believed his idea theoretically sound but nonetheless could not be satisfied with anything less than working proof. As Atanasoff put it, speaking of those anxious months before the prototype proved the concepts: "We had a feeling, an unhappy feeling, about vacuum tubes and we just had to see the thing really work . . . It wasn't only to wipe out my fear, it was to wipe out the fear of every man."[51]

Atanasoff's funding memorandum fulfilled its purpose despite its seeming vagueness, and about two months later the Research Council awarded him the full amount of his request.[52] When Atanasoff returned a letter of thanks several days later, he had named the project, "Calculating Machines for the Solution of Linear Systems of Equations." More important, he mentioned he had

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[50] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 318-319.

[51] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 10 July 1968, 3 and 69. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 4); also, J. V. Atanasoff, transcript of interview with B. Kaplan, Smithsonian Institution, 17 July 1972, 48-50. Smithsonian.

[52] E. W. Lindstrom, Chairman, Council on Research, Iowa State College, letter to J. V. Atanasoff, 18 May 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 24).

already found "a very promising student to assume this fellowship."[53] Indeed he had, as "one of the best things that could have happened to the project," Atanasoff had hired Berry.[54]

Atanasoff had asked Harold Anderson, a professor of electrical engineering, to suggest a student who might assist with the ABC. Atanasoff wanted someone capable of grasping the new electronic arts involved, but who also had practical electrical and mechanical skills. Without hesitation, Anderson recommended Berry, a graduating senior in electrical engineering planning to continue for a Master's degree. Upon meeting Berry a day or two later, Atanasoff concurred.[55]

The early lives of Atanasoff and Berry paralleled in certain aspects; notably, both were eldest children of largely self-taught electrical engineers. Clifford Berry's parents grew up on neighboring farms near Gladbrook, Iowa. His father, Fred Berry, completed tenth grade before dropping out of school to take employment with the local telephone company. He left for St. Paul, Minnesota, and found a job in electrical construction. After a few years, he returned to Gladbrook and the telephone company and married Grace Strohm. Cliff was born two years later on 19 April 1918. Two brothers and a sister followed. By his eldest son's birth, Fred Berry had opened a small appliance and repair business. That made it easier to impart his enthusiasm for electrical devices, especially radio. Cliff built his first ham radio at about age eleven or twelve and became an avid radio hobbyist.

An all-American boy, Cliff was an Eagle Scout and assistant scoutmaster. He also excelled in school, like Atanasoff. He skipped fourth grade and graduated from high school at the top of his class at age fifteen. Advanced beyond his years in some ways, he was nonetheless exceedingly quiet and shy, so his mother kept him in high school an extra year to mature socially. The murder of his father had not helped. The family moved to Marengo, Iowa, when Fred Berry became a division manager for the Iowa Power Company. A fired ex-employee shot and killed him when Cliff was not yet fourteen. Cliff thereafter took over many family duties formerly handled by his father. His youngest brother said he filled those responsibilities "admirably."[56] The widow and her four children

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[53] Note that Atanasoff used the word machines in his title and not machine. J. V. Atanasoff, letter to E. W. Lindstrom, Chairman, Council on Research, 23 May 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 24).

[54] Atanasoff, "Advent of Electronic Digital Computing," 241.

[55] J. V. Atanasoff, transcript of interview with H. Tropp, Smithsonian Institute, 7 June 1972, 177-178; Atanasoff, interview with Kaplan, 17 July 1972, 1.

[56] Keith D. Berry, Consulting Micropaleontologist, Concord, California, copy of letter to Robert W. Stafford, 16 August 1997. Engineering Services Group, Ames Laboratory. See Atanasoff Berry Computer (ABC) Replica Project, binder labeled "Correspondence FY' 97 to."

moved to Ames when Cliff entered ISC in 1935. Cliff worked part time at Gulliver Radio Service to help support the family.[57]

Atanasoff and Berry had different personalities despite whatever similarities in backgrounds they shared. Characteristics of the two can perhaps be epitomized by the observation that while Atanasoff rubbed some people the wrong way, everyone liked Berry. A student who helped with the ABC recalled that Berry, not surprisingly, had greater patience.[58] Atanasoff was all business, although it is unfair to say he had no sense of humor. Berry, even if normally quiet, had a lively sense of humor and streak of mischievousness.

As an example, Berry loved classical music. Furthermore, he happened to be dating Atanasoff's secretary, Jean Reed. Reed had lived most of her life with her widowed mother in Ames and graduated from ISC in home economics. She taught high school for a year in a nearby small town, but returned home because she found teaching did not appeal to her. She then went to work as a secretary in the ISC English Department and met Berry on a blind date to a picnic in October 1941. She found him waiting the following morning in front of her office to ask for another date. The position with Atanasoff opened up because of Project X, the secret NDRC project. By then she and Berry were seeing each other regularly. So she might enjoy the records he played in his basement alcove workshop, Berry installed a remote speaker in her desk. However, since Reed shared an office with Atanasoff, who did not like classical music, she had the speaker on only in his absence. The office had to be kept locked because of files for Project X, so she hastily turned off the music at the sound of a key in the lock. Atanasoff never caught on, as far as she knew.

Whatever their differences, Berry, no less than Atanasoff, was an intense and deeply intelligent man. Berry won widespread recognition for his electronics skills, and graduate students went to him for help, which he gave freely. Some people who learned of the ABC after Berry became involved assumed it embodied mostly his genius, so capable was he and so completely did he take over responsibilities. Atanasoff stayed more active than those people understood, but largely behind the scenes. Notably, he more than Berry maintained vendor contacts and searched for funding.

Reed, for one, saw Berry as the true project leader. She had a pot of coffee ready each day at 10:00 a.m., and Atanasoff and the students he employed gathered in his and her office to talk over their progress. She remembered Project X taking most of the discussions. Berry participated as an

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[57] Clark R. Mollenhoff, *Atanasoff: Forgotten Father of the Computer* (Ames, Iowa: Iowa State University Press, 1988), 38-41; Jean R. Berry, "Clifford Edward Berry, 1918-1963: His Role in Early Computers," *Annals of the History of Computing* 8, no. 4 (October 1986), 361.
[58] Robert L. Mather, quoted in Berry, "Clifford Edward Berry," 368.

electronics expert, although other students had more involvement. When conversation at last moved to the ABC, however, Berry took over and even Atanasoff listened.[59]

Reed married Berry, so she might be suspected of bias. Others had a similar impression, however, including a person intimately familiar with the ABC. Robert Mather began on the project scavenging parts from old equipment to reuse. One day, Berry handed him a copy of a manuscript written by Atanasoff that provided a general description of the ABC but included electronics details. If he could master those details, Berry told him, he could have more interesting assignments. Mather passed the test and did much of the wiring on the ABC, taking his instructions and wiring diagrams from Berry. Mather saw "JV" occasionally, but Berry clearly worked with minimum supervision. As far as he could tell, Atanasoff Berry Computer is a fair name, implying as it does something of a fifty-fifty attribution. Mather, who went on to earn a Ph.D. degree in physics from the University of California at Berkeley, recognized Atanasoff as highly intelligent, but so was Berry. Either man, he believed, could have "generated any of the key concepts" in the ABC. Furthermore, Mather regarded both men as friends.[60]

Atanasoff and Berry designed the ABC, but Gross and William Mercer, another student, made initial calculations for the decimal-binary conversion table,[61] and Mather figured out some minor circuits.[62] Berry had responsibility for construction, doing some himself but also supervising the craftsmen and students who helped. They numbered six or more. For much of the project, Berry was on the books as half-time help, but Reed and Atanasoff remembered him spending far more than twenty hours per week on the ABC. He kept a cot near the computer and often worked late and stayed overnight.

Atanasoff best knew the extent of Berry's contributions to the ABC, of course. He had great respect for Berry, as Berry did for him. Atanasoff did not consider Berry simply another student or employee but a fellow scientist of extraordinary ability who gave him "great emotional advantage." Although the outlines of the ABC had been formulated by the time Berry came onboard, he

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[59] Jean Berry, Eagle River, Alaska, tape-recorded interview made over the telephone with Paul Mobley, 9 and 15 April 1998; Berry, "Clifford Edward Berry," 361-362; Jean Berry, letter to Dave Lendt, Director of Information, ISU, 21 September 1988. ISU, Community Relations.

[60] Robert Mather, Oakland, California, tape-recorded interviews made over the telephone with Paul Mobley, 2, 4, and 9 March 1998; Mather, quoted in Berry, "Clifford Edward Berry," 366-368; Atanasoff, interview with Kaplan, 10 August 1972, 50-51.

[61] Atanasoff, interview with Kaplan, 10 August 1972, 18-19; John V. Atanasoff, copy of letter to George Gross, 26 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 9).

[62] John V. Atanasoff, copy of letter to J. C. Morris, Director Office of Scientific Personnel, National Research Council, Washington, D.C., 27 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 13).

contributed "many details" important to the ultimate success of the project. In fact, for details derived after Berry began work, Atanasoff "did some, but Berry did more." Atanasoff trusted him completely, noting: if "Berry said, 'This circuit is working,' the circuit was working." Furthermore, Berry always operated the ABC. Atanasoff never did.[63]

Two things stand out as evidence of Atanasoff's high regard for Berry. First, he decided that the computer he conceived and then built with Berry should be remembered as the Atanasoff Berry Computer. Second, he and Berry signed an indenture stipulating that Berry assist with filing a patent application. Berry also agreed to forfeit his right to file for claims independently. In return, he was to get 10 percent of all gross income that Atanasoff derived from the ABC. In fact, Atanasoff probably could have claimed all rights to the ABC had he chosen to do so. The underlying ideas were his, after all, and he was the professor and Berry the student. Furthermore, Atanasoff had to pay patenting and other legal fees, but the indenture specified that Berry's portion of income came free and clear.[64] Berry therefore would have received more than 10 percent of profits, had there been any, and indeed, Atanasoff anticipated that patenting costs could have been high. Berry therefore might actually have made more money than Atanasoff. All this suggests that Atanasoff credited Berry with a large role in the project

Atanasoff wanted to start work immediately once Berry agreed to assist in spring 1939. He had by then roughed out the designs of the principal parts of the ABC. He had even built a functioning model of the spark units for input and output of binary data.[65] He had to wait until fall for his grant to become available, however, so Berry worked meanwhile at the Ames Electrical Products Company.[66] The men met several times over the summer to discuss the project and study the crude sketches Atanasoff made. Atanasoff claimed a small, cramped workspace in the basement of the

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[63] Atanasoff, interview with Tropp, 7 June1972, 175-184; Atanasoff, interview with Kaplan, 17 July 1972, 1-6.

[64] Atanasoff, interview with Tropp, 7 June 1972, 185 and 190; John V. Atanasoff and Clifford E. Berry, "Indenture," 6 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 24).

[65] Gross, letter to Atanasoff, 19 August 1940; Alden H. Ryan, Statement of evidence of conception of the electric spark method of data input and output, 10 July 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 12).

[66] *Honeywell*, "Transcript of Proceedings," 1,745; "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968. ISU, Parks, "John Vincent Atanasoff Papers" (box 27, folder 5); James H. Buck, essay on C. E. Berry, circa 22 November 1986. ISU, Parks, "Clark Mollenhoff Papers, 1968-1990" (box 1, folder 6).

Physics Building, and construction of a prototype began mid-September based on his drawings. Berry did not contribute to the design of the prototype, although he helped select its components.[67]

The prototype incorporated essential elements of the ABC but on a scale small enough for the entire unit to rest on a table. It contained eleven vacuum tubes, including five twin triodes and four pentodes, a five-element tube with two grids. The ASM of the prototype used eight of the tubes.[68] An old washing machine motor served as the timing mechanism and drove the memory. The memory consisted of a ten-inch Bakelite disk with fifty capacitors attached, twenty-five per side, arranged radially and equally spaced, except for a gap of sixty degrees to allow for certain control operations.[69] The prototype memory rotated at sixty revolutions per minute, the same rate as that in the ABC. Berry input data by touching the terminals of the capacitors with charged leads, or more conveniently, with a special "converter" he contrived. He read data using an oscilloscope or voltmeter.[70] Besides integral mechanisms for data input and output, major components of the ABC missing from the prototype were a method for automatic conversions of decimal and binary numbers and a full complement of controls.

Atanasoff and Berry completed the prototype well before Christmas, probably in November, although they began testing as early as October. Not only could the prototype do additions without error, the memory and associated circuits stored and regenerated information without glitches in twenty-four hour trials.[71] Atanasoff wrote of the prototype to an acquaintance on December 7 as follows: "We began actual construction about September 15th and since that time have been able to put one of the 20 computing elements into operation. It works very well and the structure is so simple that I anticipate no difficulties other than financial ones in completing the machine (the ABC)."[72]

As this statement suggests, Atanasoff had intended to incorporate components of the prototype into the ABC as part of one of twenty parallel-computing elements for solving equations

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67 Atanasoff, interviews with Halladay, et al., 9 July 1968, 57-58 and 8-9, and 10 July 1968, 48; Atanasoff, interview with Tropp, 1 May 1972, 91.
68 Atanasoff, "Advent of Electronic Digital Computing," 242-245. See, in particular, "Figure 1. Atanasoff digital computer prototype. (Artist's conception by Thomas J. Hayes, South Bend, Indiana)," 244.
69 Atanasoff, interview with Halladay, et al., 9 July 1968, 39-40.
70 Atanasoff, "Advent of Electronic Digital Computing," 244; *Honeywell*, "Transcript of Proceedings," 2,870-2,871.
71 Atanasoff, interview with Halladay, et al., 9 July 1968, 5-6; John Vincent Atanasoff, Monrovia, Maryland, transcript of tape-recorded interview with William R. Turner, 27 October 1986, 13. ISU, Parks, "John Vincent Atanasoff Papers" (box 20, folder 3).
72 J. V. Atanasoff, copy of letter to W. E. Milne, Department of Mathematics, Oregon State Agriculture College, 7 December 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 15).

sets to nineteen unknowns. He and Berry had been planning for the ABC concurrently with construction of the prototype and spent much of their time during the fall researching possible components. However, the men gained confidence with the unqualified success of the prototype. They now recognized that electronic digital computers had potential beyond what they had envisioned.[73] They therefore rethought the ABC, which was in fact already under construction. As one consequence, they did not reuse the prototype but disposed of it several months later when enough of the ABC was completed to allow its demonstration. They needed the space the prototype occupied.[74]

As it were, Atanasoff and Berry maintained the original purpose of the ABC, but changed its design to increase the number of unknowns it could handle to twenty-nine. Thus, instead of twenty elements, it needed thirty, including one for equation constants. Furthermore, Atanasoff and Berry discovered they could use smaller capacitors than anticipated [75] and decided to mount them inside drums instead of on disks to save money and make the ABC more compact.[76] The new capacitors also allowed redesign of the ASMs to contain fewer and different vacuum tubes.[77] After experimentation and research, the men selected the twin-triode 6C8G tube for its operating characteristics and compactness. Each ASM needed thirteen triodes, so they used seven of the vacuum tubes. One triode in each ASM therefore sat idle.[78] The ABC contained several hundred vacuum tubes plus thirty thyratrons, a gas-filled tube used in the binary-card punch units.[79]

The 6C8G was intended as a "receiver," or radio, tube,[80] and thus not particularly suited to digital service. However, neither was any of the great variety of standard production tubes. In analog circuits, a vacuum tube needed a long, linear, and upward-sloping middle operating range so that the gain in output current at the anode corresponded closely to a widely varying input voltage at the grid. That is, a vacuum tube needed to become conductive upon reaching a cutoff grid signal and then

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[73] Atanasoff, "Advent of Electronic Digital Computing," 242 and 247.
[74] Atanasoff, interview with Halladay, et al., 10 July 1968, 16.
[75] Atanasoff, interview with Tropp, 11 May 1972, 149.
[76] J. V. Atanasoff, copy of letter to D. Howard, Aerovar (sic: Aerovox) Corporation, 21 December 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 2, folder 3).
[77] Atanasoff, interview with Tropp, 11 May 1972, 149-150.
[78] Berry and Atanasoff eventually used the fourteenth tube as a "floating grid." Atanasoff, interview with Kaplan, 10 August 1972, 20-21.
[79] The ABC contained approximately 525 triodes. Thyratrons served well for spark punching because, once conducting, current continued to flow until the signal voltage went to zero. Moreover, thyratrons handled large amounts of currents better than vacuum tubes. Burks and Burks, *The First Electronic Computer*, 45-46; Atanasoff, "Advent of Electronic Digital Computing," 248 and 251; Atanasoff, interview with Kaplan, 23 August 1972, 15-17.
[80] Atanasoff, "Advent of Electronic Digital Computing," 242-242.

allow proportionally more current to pass as the signal became more positive over a broad range. On the other hand, a vacuum tube in digital applications served best if it simply snapped on upon reaching a trigger voltage since there were only two of interest: high and low. A vacuum tube with a sharply vertical transitional range functioned best. Digital and analog applications thus demanded quite different tubes. It might seem that digital service was less exacting, but it proved more difficult to make vacuum tubes for it. No manufacturer did for years after World War II. The problem drove IBM to design and manufacture its own tubes beginning in the late 1940s.[81]

If finding satisfactory vacuum tubes posed a problem for Atanasoff and Berry, so did how to incorporate them into switching circuits. They were in uncharted territory. As a fundamental problem, the performances of tubes varied widely, even within the same type.[82] Moreover, early electronic logic circuits, including those in the ABC, were composed of vacuum tubes wired into resister networks so that some grids had more than one input. This became known as majority logic.[83] The maximum number of inputs to a vacuum tube grid was called fan-in. The maximum number of outputs from a plate was called fan-out. Majority logic simplified circuits and made particular sense when resisters were cheap and tubes expensive. The downside was decreased stability. An initially well-behaved majority logic circuit could become unreliable as resisters and tubes aged. That probably posed little problem for the ABC, operating as it did at 3,600 pulses per minute. Even so, Berry took pains to measure all resisters and carefully match them in parallel networks. As important, Atanasoff limited fan-in to three and fan-out to four.[84] Thus, although Berry conceived of a theoretically sound ASM with just five twin-triode vacuum tubes, he and Atanasoff decided not to use it because of concerns about long-term stability.[85] As it were, the ABC could have operated satisfactorily at higher speeds, but had it been run at anything like the clock rate of postwar computers its circuits might have failed. As computers became faster, combinational logic evolved to one input per vacuum tube grid.

Atanasoff and Berry did not apply Boolean algebra to the design of logic circuits. It did not occur to them, although Atanasoff was familiar with it. Rather, they designed circuits intuitively, or

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[81] Bashe, et al., *IBM's Early Computers*, 65-67.
[82] Burks, "Electronic Computing Circuits of the ENIAC," 757.
[83] J. A. Rajchman, "RCA Computer Research—Some History, and a Review of Current Work," *RCA Engineer* 8, no. 6 (April/May 1963), 6.
[84] Atanasoff, interview with Kaplan, 10 August 1972, 9; Burks and Burks, *The First Electronic Computer*, 40-43, 311, and 323.
[85] Atanasoff, interview with Tropp, 1 May 1972, 93; Atanasoff, interview with Kaplan, 17 July 1972, 2-3 and 8-11; Atanasoff, interview with Kaplan, 10 August 1972, 9-10.

as Atanasoff put it, "by main strength and awkwardness."[86] While electronic circuits could be troublesome to design,[87] the logic behind those in the ABC was not difficult, even if "hit and miss."[88] In fact, none of the early computer builders used Boolean algebra, even after Shannon's prewar work became generally known.[89] In a lecture in 1946, Eckert explained why: "As a practical matter, circuits which are simple enough to be usable in practical machines, are usually so easily analyzed that recourse to Boolean algebra is not necessary." [90] Boolean algebra became important as combinational logic circuits gained complexity. Incidentally, combinational logic circuits are defined as those containing no memory elements. Boolean algebra cannot be used for logic circuits with memory, such as those with flip-flops.[91]

Atanasoff and Berry built the prototype with whatever parts were convenient, but they intended the ABC for rigorous long-term duty. It and its components had to be considered carefully. For example, early in 1939 Atanasoff began investigating capacitors,[92] normally low-cost and reliable electronic circuit components produced by the millions. Berry continued the inquiries through the fall[93] and provided vendors with the following specifications: "small paper condensers . . . (that) must lose due to internal leakage, not more than half their charge in ten seconds, or even more slowly, and further that they be relatively long-lived. Small physical size is of considerable importance."[94] Many types of capacitors held sufficient charge for longer than ten seconds, as it turned out.[95] However, Atanasoff and Berry substantially complicated the application by deciding to mount 1,600 capacitors inside each of two cylinders 8" diameter by 11" long.[96] Worse, due to limited space, they proposed

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86 Atanasoff, interview with Tropp, 11 May 1972, 135-136.
87 Burks and Burks, *The First Electronic Computer*, 294.
88 Atanasoff, interview with Halladay, et al., 10 July 1968, 57; Atanasoff, interview with Kaplan, 10 August 1972, 5-6.
89 Burks and Burks, *The First Electronic Computer*, 348.
90 J. Presper Eckert, Jr., "Types of Circuits—General," 18 July 1946; reprinted in *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), 188.
91 Patterson and Hennessy, *Computer Organization and Design*, B4-B5.
92 J. V. Atanasoff, copy of letter to John E. Fast and Co., 5 January 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
93 Atanasoff, interview with Halladay, et al., 9 July 1968, 10.
94 For example, Clifford E. Berry, copy of letter to Cornell-Dubilier Corporation, 28 September 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
95 Atanasoff, "Advent of Electronic Digital Computing," 242; *Honeywell*, "Transcript of Proceedings," 1,736.
96 Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 321.

using uncased capacitors.[97] They nonetheless demanded that the capacitors maintain integrity for years.[98] Vendors balked, noting as one did that the application did, "not come under our usual routine capacitor requirements."[99] Another vendor warned that condensers, "unless properly sealed, will pick up moisture, thereby giving a short life."[100] Atanasoff and Berry did install uncased capacitors but took precautions that satisfied the manufacturer, including packing them in wax and operating at low voltages.

Excellent engineers, Atanasoff and Berry took little for granted and made reliability a primary consideration. They gave the ABC a conservative design to ensure its trouble-free operation. The small number of vacuum tubes and simplicity of circuits constituted a first defense against failures. The foremost worry was vacuum tube life, so Atanasoff and Berry designed circuits for lower-than-rated plate and filament voltages. Furthermore, they fabricated a test set that allowed them to "age" tubes and test ASMs under variable operating conditions before installation. As a consequence, tubes did not fail in the computer through many hours of testing.[101] Moreover, they limited memory circuits to 10 percent of rated voltage to extend the life of capacitors. The supplier assured them that the condensers in the ABC should have functioned indefinitely.[102]

The design for reliability included means for easy repairs, since all machines sooner or later experience breakdowns. To that end, Atanasoff and Berry installed two spare bands of capacitors inside each memory drum.[103] As another example, the ASMs were built as small, identical modules that could be replaced quickly.

On the other hand, Mather believed that the emphasis on keeping costs low came at some sacrifice of reliability. He noted specifically the dependence on cheap but transient student labor.[104]

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97 John V. Atanasoff, copy of letter to D. Howard, Aerovar (sic: Aerovox) Corporation, 21 December 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
98 Clifford E. Berry, copy of letter to D. Howard, Aerovox Corporation, 21 October 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
99 G. V. Peck, P. R. Mallory & Co., letter to J. V. Atanasoff, 15 December 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
100 D. Howard, Aerovox Corporation, copy of letter to John V. Atanasoff, 28 December 1939. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 7).
101 Atanasoff, interview with Tropp, 11 May 1972, 166-167; J. V. Atanasoff comments to C. G. Call in, "Legvold Interview," 21 September 1967. ISU, Parks, "Clark Mollenhoff Papers, 1968-1990" (box 8, folder entitled "Call Memos").
102 Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 330.
103 Atanasoff, interview with Tropp, 11 May 1972, 174.
104 Mather, quoted in Berry, "Clifford Edward Berry," 366.

As for Mather, himself a transient student, Atanasoff considered his skills in wiring, "comparable in quality to the wiring done by experts in the telephone fields."[105]

Otherwise, the electromechanical clock system of the ABC might have given more problems than an electronic equivalent. In particular, the transfer of electronic signals by mechanical commutation seems likely to have been vulnerable to wear. With further consideration, Atanasoff regretted that he had not chosen stainless steel for wear points instead of brass.[106] Brass is normally used in such applications but stainless steel has superior wear resistance.

All in all, the ABC involved compromises that proved effective. Atanasoff wanted magnetic memory but settled on capacitors. He compromised on fan-in and fan-out of logic circuits. He considered an electronic clock but used instead an electric motor. He employed relays in some controls instead of vacuum tubes. He made the ABC special instead of general purpose. He compromised in each case to keep the project within time and money constraints. Yet, none of these decisions seriously hindered capabilities of the ABC to fulfill its purpose. For example, Atanasoff and Berry certainly could have built an electronic clock, but the major bottleneck would still have been the import and export of data, just like the ENIAC.[107] Moreover, had the ABC been made general purpose, it would have undoubtedly weakened its capabilities to solve partial differential equations, given limitations in memory technologies and applied mathematics. The ENIAC is again a case in point. Even von Neumann preferred solving partial differential equations as sets of linear algebraic equations. The IAS computer did not immediately change that.

Had Atanasoff and Berry the resources to expand the ABC into something like the NOL or IAS computers, it would have been worthwhile. The ABC already incorporated essential features of a true computer except for means of easy reprogramming. Nonetheless, the ABC had significant capabilities at an amazingly small cost. Atanasoff could have spent much more money and had little extra to show for it, just as with the ENIAC. By making sound engineering decisions, Atanasoff and Berry produced a groundbreaking computer that could fulfill essential needs, but that also provided the direction for continued innovation.

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[105] Atanasoff, copy of letter to Morris, 27 April 1942.

[106] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 11 July 1968, 16. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 2).

[107] Burks and Burks, *The First Electronic Computer*, 48; Atanasoff, interview with Kaplan, 10 August 1972, 16-17; Atanasoff, interview with Kaplan, 23 August 1972, 50-51; J. V. Atanasoff, New Market, Maryland, transcript of interview with H. Tropp, 24 May 1972, 123-124. Smithsonian.

The importance of vendors to engineering projects is often overlooked. They provide not only products but also expert advice on how the products can be used. For the ABC, Atanasoff not only got valuable information from suppliers, he received significant financial aid in the form of price breaks. In dealing with vendors, Atanasoff sometimes gave a brief account of the ABC, shrewdly hinted at prospects for future sales, which assumed that the ABC might be manufactured in large numbers, and led the vendor into making the connection. For example, he wrote one manufacturer: "it is quite possible that machines of this type will have commercial applications. The manufacture of such machines using as they do large numbers of condensers would be of interest to you."[108] Indeed it was. One representative responded that his company had great interest and wanted to cooperate in "every respect."[109] Another vendor offered Atanasoff prices for capacitors that were, "somewhat less than we would usually quote under the circumstances, but if we could contribute in some way to your development, we would be pleased indeed."[110] Despite such enthusiasm from several capacitor manufacturers, Atanasoff found only one willing to risk selling them uncased.[111]

Directness better suited Atanasoff, of course. After asking for technical assistance from one resister manufacturer, he added: "we are building a complicated machine for which we will require 600 or more resisters . . . While the machine we are building is designed for research purposes it may have some commercial application. I am wondering if you would care to assist Iowa State College in the construction of this machine to the extent of granting us lower prices than we can secure in the open wholesale market."[112]

Atanasoff made a similar pitch to R. M. Bowie of Hygrade Sylvania Corporation, a vacuum tube manufacturer.[113] Bowie subsequently arranged to sell him 6C8G vacuum tubes for forty-eight cents apiece, considerably below market price.[114] Bowie then reminded Atanasoff: "Let us know when you get to the stage of commercialization and we shall be pleased to submit you an attractive quotation on tubes."[115] Although not to that stage yet, Atanasoff let him know he had immediate need

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[108] Atanasoff, copy of letter to Howard, 21 December 1939.
[109] Howard, copy of letter to Atanasoff, 28 December 1939.
[110] Peck, letter to Atanasoff, 15 December 1939.
[111] Atanasoff, interview with Tropp, 11 May 1972, 143-144.
[112] John V. Atanasoff, copy of letter to Harry A. Ehle, International Resistance Company, 4 January 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 6).
[113] John V. Atanasoff, copy of letter to Dr. R. M. Bowie, Hygrade Sylvania Corp., 4 January 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 6).
[114] R. M. Bowie, Hygrade Sylvania, copy of letter to John V. Atanasoff, 18 January 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).
[115] R. M. Bowie, Hygrade Sylvania, copy of letter to John V. Atanasoff, 14 June 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).

for additional tubes, asserting as a sweetener: "If this machine (the ABC) is manufactured in any considerable number, the tube and condenser manufacturers stand to do a good business."[116]

Atanasoff actually had a long acquaintance with Bowie, who took the first Ph.D. degree in physics from ISC in 1933. Atanasoff did not hesitate asking for help from any vendor, however. After being solicited by Atanasoff, a representative of Raytheon Production Corporation responded that, "management is definitely interested in your work."[117] Raytheon subsequently gave him one hundred 6C8G vacuum tubes.[118] As another example, Atanasoff tempted IBM with a low-key, cryptic come on: "I believe we have some ideas that will ultimately prove useful in the computing art." He then asked to be allowed to purchase several hundred of a type of brush commonly used in EAM equipment.[119] IBM shipped five hundred or so at no charge. In announcing the first shipment, Clement Ehret, Director of Market Research, indicated IBM's interest in the ABC. While unclear on whether it was a continuation of Atanasoff's earlier tabulator attachment project or an entirely new machine, Ehret noted that either way IBM hoped to learn more and witness a demonstration.[120]

Support from industry contributed significant savings to the ABC. Scavenging parts from old equipment gave additional savings. Atanasoff estimated that a full-cost copy might have run $10,000 to $15,000,[121] instead of the $3,600 the ABC probably cost.

The heart, or as Atanasoff preferred, the brains, of the ABC were thirty ASMs operated in parallel to solve simultaneous equations with up to twenty-nine unknowns using a variation of the already well-known Gaussian elimination method. The ABC dealt with two equations at a time to reduce the original square matrix to a triangular one ending in one equation and one unknown. Instead of solving for the unknown, the operator reversed the process and paired the last equation with one of the two prior equations in two unknowns. That resulted in a new equation with one

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[116] J. V. Atanasoff, copy of letter to R. M. Bowie, Hygrade Sylvania Corporation, 19 June 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).
[117] N. B. Krim, Raytheon Production Corporation, copy of letter to John V. Atanasoff, 11 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).
[118] J. V. Atanasoff, copy of letter to N. B. Krim, Raytheon Production Corporation, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).
[119] J. V. Atanasoff, copy of letter to R. R. Walker, IBM, Chicago, 12 January 1940; J. V. Atanasoff, copy of letter to Clement Ehret, IBM, New York City, 24 January 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).
[120] Clement Ehret, Director Market Research, IBM, letter to J. V. Atanasoff, 8 February 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).
[121] John V. Atanasoff quoted in a transcript for "Iowa State Today," a radio news program hosted by Ione McNay, 1 May 1942, 2. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 5).

different unknown, which was itself paired with a previous equation for further solution. The ABC continued working backwards until every unknown was isolated.

To begin the solution of a system of equations, the operator used a standard IBM keypunch to record the original decimal coefficients into eighty-column IBM punch cards.[122] Each coefficient could have fifteen or sixteen places. Thus, one card could hold five coefficients, and twenty-nine unknowns required six cards per equation. The punched cards were entered with a special decimal card reader. The ABC transformed the decimal numbers into their binary equivalents with a rotating drum incorporating a mechanical conversion table. The digital signals emanating from the table were printed into special cards with the binary spark-punch device. All coefficients for one equation fit into one binary card.

After the operator converted the coefficients for all equations, the result was a stack of cards with charred spots representing binary numbers. The operator fed those back into the ABC using the binary card reader. The reading unit operated much like the punch but at a lower voltage, because its purpose was not to char the paper further, but to detect differences in resistance caused by the charred spots. The punching voltage could be as high as 5,000 volts, the reading voltage as little as one-fourth that.[123] The operator worked with two equations at a time, feeding them into the ABC, one after the other, and each was stored on one of the two memory drums. Each coefficient of forty-nine binary digits and a sign got stored as electrical charges in one of thirty-two bands of fifty capacitors each that were arranged around the circumference of each drum. Two bands per drum served as spares.

The memory drums rotated at one revolution per second. The capacitors were connected at the surface of the drums to metal studs arranged precisely six degrees apart except for a gap of sixty degrees for control operations. Atanasoff referred to each band as an abacus and the memory drums as abaci. Metal brushes swept the studs with each rotation and transmitted stored numbers as sequential streams of binary voltages. The signals were either reentered in reenergized form through another set of brushes or routed to the ASMs to use in calculations with the number streams coming from the second memory drum.

The operator selected a variable for elimination by inserting a plug to make electrical connections. All coefficients from one equation were then simultaneously added to (or subtracted

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[122] Otherwise, the ABC used no major pre-manufactured components. Atanasoff, interview with Tropp, 11 May 1972, 153.
[123] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 324-326.

from, as appropriate) the corresponding coefficients in the second equation. The process occurred as many times as necessary to eliminate the designated variable. Remaining coefficients were then printed with the binary punch, and the next set of cards containing the variable fed into the ABC. And so on the process went until the designated variable had been eliminated from all equations. The operator then selected the next variable to eliminate until the set was finally reduced to one equation and one unknown. As noted, the operator then had the ABC work backwards to isolate the other unknowns. Final answers appeared as decimal readouts on a mechanical counter.[124]

Much of the operation of the ABC was automatic but nonetheless involved enormous amounts of data throughput, first as decimal numbers, but mostly binary. Atanasoff developed the binary input and output units because IBM mechanisms were not available to him, but more important, because he wanted faster data throughput than possible with ordinary punched-card equipment.[125] Berry chose the development of these units as the subject of a Master's thesis. For a thorough description of the design and operation of the ABC, see *The First Electronic Computer* by Burks and Burks.

Construction of the ABC began in November 1939, although its design continued into summer and beyond.[126] To get fabrication moving, Atanasoff estimated the ABC's ultimate size, purchased lengths of structural steel, and had a framework welded together, although it was not finished in all details until April. It amused Berry that Atanasoff built the framework before they really knew what needed to go into it. Others also found it amusing, and Atanasoff got kidded for flying by the seat of his pants in this instance. Considering Atanasoff, however, perhaps it should not be attributed to dumb luck that the framework turned out the perfect size.[127]

Under Berry's supervision, and because of his "ease in working with materials," and because of his and Atanasoff's "smooth, and easy, and systematic cooperation,"[128] the ABC came together faster than Atanasoff had expected. In June 1940, he made the following report:

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[124] Atanasoff, interview with Kaplan, 23 August 1972, 32-46.
[125] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 325.
[126] Atanasoff, interview with Halladay, et al., 9 July 1968, 13 and 37.
[127] Atanasoff, "Advent of Electronic Digital Computing," 247-248; "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968; Berry, letter to Richards, 12 July 1963; Atanasoff, interview with Tropp, 11 May 1972, 142; *Honeywell*, "Transcript of Proceedings," 2,422.
[128] Atanasoff, interview with Tropp, 7 June 1972, 184.

> Work on the computing machine as (sic) proceeded in a way that is very gratifying. Although we are still designing as well as building, the details of design for most of the machine are completed and a large fraction of these details have been tested in natural operation. Perhaps half of actual construction on the machine has been completed. During the summer, I have been having a full time assistant, Mr. Berry, who worked has (sic) half-time research assistant on the project last year. He combines in a way that I have scarcely observed before, a high degree of mental dexterity and manipulative skill with a keen theoretical understanding.[129]

The going was not all smooth, of course. As one setback, upon advice from a supplier's engineer, Atanasoff and Berry tried fabricating memory drums from cast Bakelite cylinders. They broke the first two cylinders while drilling holes in them. They purchased two more and cracked them the same way. Disgusted, Atanasoff disregarded the engineer's advice and bought two phenolic cylinders, that is, laminated paper impregnated with plastic resin, which worked fine.[130] The drums were finished by mid-August, as were all thirty ASMs and associated controls that Atanasoff termed "holder-shifter-circuits."[131] As indicated above, Atanasoff estimated that half of the ABC had been finished by June 1940, about seven months after starting.

The downside of pushing ahead of schedule was that money became depleted faster. In January 1940, Atanasoff expressed his anxiety to a friend: "I am faced with the necessity of raising more money. My hopes are that I will be able to secure enough money locally to prevent the interruption of the construction."[132] Harold V. Gaskill, Dean of Science, provided a slight respite with $150 for supplies from his funds. In April, Atanasoff went back to the ISC Research Council for additional money. An excerpt from his request read as follows:

> I have no inclination to minimize the difficulties inherent in this development (the ABC). Most people to whom I have talked about this project have been surprised that we should undertake such a huge machine. A few, among them Prof. Urey of Columbia University, have been intrigued by the research possibilities of such a piece of equipment and have given us much encouragement and advice. We were well aware of these difficulties at the time we made the initial request from the Research Council and I only promised Prof. Lindstrom (Research Council Chairman) that I would try to place one computing element of this

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[129] Atanasoff, letter to Bowie, 19 June 1940.

[130] Atanasoff, interview with Tropp, 11 May 1972, 146-147; Atanasoff, interview with Kaplan, 23 August 1972, 13-15; *Honeywell*, "Transcript of Proceedings," 2,419-2,421.

[131] Atanasoff, "Computing Machine for the Solution of large Systems of Linear Algebraic Equations," 330; "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968.

[132] J. V. Atanasoff, copy of letter to A. E. Brandt, Acting Head, Soil and Water Conservation Experiment Station, U.S.D.A., 5 January 1939 (sic: 1940). ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).

> machine in operation during the year. In spite of my preliminary estimate, I could not convince myself that any substantial progress could be made on this project with the means that the Research Council could afford to grant us.
>
> Again I must not let my enthusiasm convince you that the difficulties are all overcome. However, the one computing element was in operation before January 1. We knew then that the fundamental principle was workable, simple, and surprisingly cheap. Since January 1 we have spent our time making plans and doing construction work on the entire machine. Curiously enough, the most irritating problem has been concerned with getting numbers into and out of the machine; the complication of the operations is so great that no keyboard pencil and paper methods are possible. Many new problems in machine and electrical design have been met. Recently numerous parts have been completed and finished assemblies for the entire machine are commencing to take form. I am more convinced than ever that our ideas are sound and suitable for the solution of this important problem in applied mathematics.[133]

Atanasoff was careful what he said about the ABC, aware that it could impact his standing for a patent. He nonetheless discussed it with a number of people outside of ISC besides vendors, as the passage indicated. He had special reason for mentioning Urey. Harold C. Urey, a physical chemist, won the 1934 Nobel Prize in chemistry for the 1932 discovery of the hydrogen isotope deuterium. Urey was a frequent visitor to ISC and friend to Atanasoff, who talked with him freely. An endorsement by Urey carried substantial weight at a time when Atanasoff suspected some people believed him "half-crazy" for attempting the ABC.[134] Note, too, that Atanasoff and Berry recognized early that the binary spark-punch units were going to cause the most trouble of any part of the ABC.

In this second go around, Atanasoff asked for $750 from the Research Council. It gave him $700 and a warning that there might not be any more to follow.[135] The small difference scarcely mattered, however. He told the Council that his, "estimate of the total cost of the machine has been greatly reduced,"[136] but even so, he believed he needed several thousand dollars to finish the ABC. Moreover, with Berry working full time during the summer, money intended for the academic year would be gone by January.[137] Atanasoff was thus forced to seek outside funding.

Manufacturers of EAM equipment were an obvious source of money, since Atanasoff recognized the ABC as advancing their machines. He therefore cautiously approached IBM and Remington Rand to fund his work. His overture to Remington Rand read as follows:

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[133] Atanasoff, letter to Lindstrom, 9 April 1940.
[134] Atanasoff, interview with Halladay, et al., 10 July 1968, 28-31 and 43.
[135] E. W. Lindstrom, Chairman, Council on Research, Iowa State College, letter to J. V. Atanasoff, 24 April 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[136] Atanasoff, letter to Lindstrom, 9 April 1940.
[137] J. V. Atanasoff, copy of letter to R. E. Buchanan, Dean of Graduate College, ISC, 16 October 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

> I have made and am making some developments in the computing machine art which may be of interest to you since they apply rather specifically to tabulating machines. I believe my developments will enable one to build a computing machine which will perform all the operations of the standard tabulators and many more at much higher speeds and at a much lower cost of construction.
>
> I fully realize that this is a strong statement. However, I have one computing element of such a machine in operation and it works very satisfactorily.
>
> If you are interested in such developments please state what you consider is equitable basis to be followed in making disclosures to your company.[138]

Atanasoff was deliberately vague because he did not want to disclose much without a signed agreement that ensured his rights. His claims nevertheless caught the attention of Remington Rand and further stimulated the interest of IBM. However, the corporations had legal positions to consider, and both, especially IBM, asked Atanasoff to first sign releases he considered too one-sided in their favor.[139] In the case of Remington Rand, Atanasoff complained that its contract: "would furnish your company with all my information without any corresponding obligation on your part and would perhaps enable you to resuscitate some old investigation and file an application on it making my application the junior in the resulting interference." Not giving up, Atanasoff coaxed with a cogent prophecy: "I am rather sure that your firm will sooner or later by very interested in this type of machine. Its relative simplicity and high speed of operation constitutes advantages which will be hard to overcome."[140]

In reply, Remington Rand noted, probably justifiably, that its contract format had been established for good reason: "because of experience with such matters over a period of years. Our own engineering and development departments have been working on projects for some time, endeavoring to achieve the same results which you are pointing toward. It might conceivably be that we both are, or have, traveled similar paths." Remington Rand knew, as did IBM, that a truly novel idea is rare without someone, somewhere, having a similar one. Through incessant searching for new technologies, the office appliance companies might have already possessed the essence of what

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[138] John V. Atanasoff, copy of letter to Market Research Division, Remington Rand, Inc., Buffalo, New York, 6 April 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 3).
[139] In the case of IBM, see the form entitled "To All Persons Who Desire to Submit Suggestions to the International Business Machines Corporation." ISU, Parks, "John Vincent Atanasoff Papers" (box 24, folder 4).
[140] John V. Atanasoff, copy of letter to T. F. Allen, Vice-President, Remington Rand Inc., New York City, 6 September 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 3).

Atanasoff had to sell. Remington Rand assured Atanasoff of its good intentions and keen interest but refused to modify its contract.[141]

Atanasoff had greater interest in IBM in any case. He told Ehret that, "there is nothing that would please me more than to secure the cooperation of your company in the mutually advantageous development of these ideas (of the ABC) on any reasonable basis."[142] To that end, he visited IBM's "World Headquarters" in New York City in April. Actually, he made a number of stops on an itinerary to investigate funding.[143]

He first went to Washington, D.C., to see Vannevar Bush at the Carnegie Institution. Endowed by steel magnate Andrew Carnegie, the Carnegie Institution gave away over $1.5 million each year for research. As its president, Bush had considerable discretion in making awards.[144] As discussed, he listened politely but offered no support.[145]

Why Bush did not have greater interest is a matter for speculation. Certainly he was preoccupied with national defense. Concerned about the coming war he thought inevitable, Bush worried about the U.S. being unprepared to give its soldiers the sophisticated weaponry they would need. In June, several weeks after meeting Atanasoff, Bush formally proposed the NDRC to aid development of those weapons. President Roosevelt immediately approved the bold plan. The NDRC supplemented research conducted by the military but had broad powers in its own right. As chairman, Bush answered directly to Roosevelt. Scientists worked under contract but in their own university or industrial laboratories.[146] The NDRC within a year consumed the efforts of over 75 percent of the nation's best physicists, including Atanasoff.[147]

Not yet having any inkling of that involvement, Atanasoff continued to explore funding possibilities. He got a more favorable reception in Washington from C. G. Smith of Raytheon.

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[141] T. F. Allen, Remington Rand, letter to John V. Atanasoff, 11 September 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 3).
[142] John V. Atanasoff, copy of letter to Clement Ehret, IBM, 6 April 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).
[143] Atanasoff left Ames on 23 April 1940. He returned about two weeks later. "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968; Atanasoff, letter to Bowie, 19 June 1940.
[144] G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: The Free Press, 1997), 83, 91, and 94-95.
[145] Atanasoff, interview with Halladay, et al., 10 July 1968, 49-50.
[146] Zachary, *Endless Frontier*, 101-102, 112-117, and 138.
[147] Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Alfred A. Knopf, 1978), 320.

Another representative subsequently contacted Atanasoff to express his company's enthusiasm for the ABC:

> We are naturally very much interested in any such machine, and are especially so in view of Dr. Smith's hopes as the possibilities of your device.
>
> If you think this machine is ready for any commercial application, we would like very much to have an opportunity to discuss it with you, and if you think there is anything we could do in the line of manufacturing or marketing such equipment, we would also like to consider that.[148]

Atanasoff needed information on thyratrons from Raytheon, but he was not ready to commit to a manufacturer until he had investigated other possible funding sources. However, Atanasoff assured the representative: "I shall try to see that your firm is treated fairly in any commercial application which my (sic) develop."[149]

Atanasoff next went to Harvard to see Howard Aiken, involved with IBM on the ASCC. The men discussed design of computers but had radically different opinions, both on how a computer should be organized and the relative merits of relays and vacuum tubes. Neither changed the other's mind. For his part, Atanasoff thought the ASCC "primitive and not very valid," "the last throb of the old era."[150]

Atanasoff then traveled to New York City. His meeting with Ehret at IBM went well, so much so, it revived his hope of finding employment with the company, although no promises were made. Atanasoff subsequently sent Ehret another employment application, noting: "I feel certain that I would enjoy working with your organization. Further I believe that I am in a position to realize the possibilities of new developments more fully than one with less background in Mathematics and the Physical Sciences." Atanasoff also expressed his conviction that the development of the computer, "represents the only escape from the mathematical intricacies of modern life."[151]

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[148] Elmer J. Gorn, Raytheon Manufacturing Company, letter to J. B. Attanasoff (sic), 2 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 3).

[149] J. V. Atanasoff, copy of letter to Elmer J. Gorn, Raytheon, 6 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 3).

[150] Aiken gave Atanasoff a copy of a bibliography listing computing machine developments. It is contained in ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20); see also, *Honeywell*, "Deposition of Dr. John V. Atanasoff," 275-277; Atanasoff, interview with Tropp, 11 May 1972, 161-166; Atanasoff, interview with Kaplan, 23 August 1972, 4-5; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 23 July 1968, 39. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 7).

[151] John V. Atanasoff, copy of letter to Dlement (sic: Clement) Ehret, Director of Market Research, IBM, 5 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

Finally, Atanasoff paid a visit in New York City to Warren Weaver, then in a hospital with a kidney infection.[152] His former professor had become director of Natural Sciences of the Rockefeller Foundation and, as such, had the enviable duty of giving away millions of dollars in old, oil money. Among those that received Rockefeller Foundation funding for research or training included many of the great names of science, such as Bohr, Heisenberg, and others worldwide. The philanthropic organization funded the Rockefeller Analyzer, then under construction at MIT, but its largest gift, $6 million, was for a two-hundred-inch telescope at the Mount Palomar Observatory in California.

Against the backdrop of the Depression, however, Weaver decided that the biological sciences offered greatest benefit to humankind. The Rockefeller Foundation, and philanthropic organizations generally, therefore shifted resources from the physical sciences to public health. Its money now promoted such laudable endeavors as worldwide control of yellow fever, malaria, and hookworms, a once common parasite that afflicted peoples in warm climates.

Admirable as that new policy otherwise was, it meant Weaver had to tell Atanasoff that he had little chance of getting the $5,000 he thought necessary to finish the first electronic digital computer. By contrast, about this time, Weaver approved $1,150,000 for physicist Ernest O. Lawrence to build a huge cyclotron at the University of California at Berkeley. Although there were already thirty-two or more cyclotrons or related nuclear accelerators in operation or under construction in the United States in 1940, atom smashers had use in medicine, particularly for fighting cancer. Lawrence, an old hand at the funding game, emphasized that in his application. He instructed Bohr that it was just "much easier to get funds for medical research."[153]

Atanasoff did not have a biological angle but did find Weaver sympathetic.[154] Weaver urged Atanasoff to present his case to other organizations that might have interest in computers. He gave Atanasoff the names of two. Moreover, Weaver told Atanasoff that if those leads did not bear fruit, then he should come back.[155]

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[152] Atanasoff, interview with Tropp, 11 May 1972, 155-157; John V. Atanasoff, copy of letter to Warren Weaver, 10 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[153] Quoted in Kevles, *The Physicists*, 274-275; also 190-193, 247-249, 267, 270-275, and 284-286; Warren Weaver, *Scene of Change: A Lifetime in American Science* (New York: Charles Scribner's Sons, 1970), 58-61 and 64-75.
[154] Atanasoff, interview with Halladay, et al., 10 July 1968, 51-52.
[155] Warren Weaver, copy of diary entry, 1 May 1940; Warren Weaver, Rockefeller Foundation, letter to J. V. Atanasoff, 23 May 1940; John V. Atanasoff, copy of letter to Warren Weaver, Rockefeller Foundation, 10 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 42, folder 9; box 26, folder 1).

Back in Ames, Atanasoff therefore applied to the Research Corporation[156] and the Committee on Scientific Aids to Learning (CSAL). Frederick G. Cottrell founded the Research Corporation. As a young, newly married chemistry instructor at the University of California, he had financial troubles and to overcome those invented an electrostatic precipitator to reduce smokestack effluvia. In controlling pollution it recovered valuable chemicals and eventually yielded large profits. However, his struggle to commercialize his invention stimulated Cottrell in 1912 to forsake real wealth and pool his patents with money from associates to endow a private corporation in which profits went to scientific or educational institutions to promote promising research. Other scientists assigned their inventions, and the Corporation supported projects in a variety of fields. In 1923, it made a grant to the Smithsonian Institute for seminal work by Albert H. Goddard in rockets. Nuclear physics became a priority in the 1930s. The Corporation funded, in total or in part, a number of nuclear accelerators, most notably for Lawrence, including the first full-scale cyclotron. It also supported related research by R. J. Van de Graaff at MIT into electrostatic generators. There was even precedence for the ABC amidst the Corporation's many projects. Around 1924, it "uncovered a marvelous calculating machine that can compute algebraically" and paid for further development.[157]

The latter invention would have been ideal for the CSAL, had it been around at the time. The Carnegie Corporation created the CSAL in 1937 to promote technologies associated with learning and thinking. Such an organization might seem tailor made for Bush, and in fact, he was a founding member and wrote its prospectus. Other members included Frank Jewett, head of the BTL, and James Conant, president of Harvard.[158] Thus, Weaver provided Atanasoff with names of two quite appropriate foundations.

The following excerpt from Atanasoff's initial letter to the CSAL is worth noting for the insight it gives to his estimate of the capacity of the ABC compared to other computing methods of the day:

> This machine will have a numerical capacity nearly six times that of the largest punched card tabulator which is, as far as I am aware, the largest computing machine ever built. At the same time its computing speed will be much greater so that what might be called the computing capacity will multiply that of the large tabulator by a factor of ten or twenty for the work for which it is designed. Its speed in the solution of systems of linear algebraic equations will be very great and here it should multiply the efforts of an expert computer with

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[156] John V. Atanasoff, copy of letter to Howard A. Poillon, President, Research Corporation, 10 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[157] Arthur A. Hammerschlag, President, Research Corporation, quoted in Frank Cameron, *Cottrell: Samaritan of Science* (Garden City, New York: Doubleday & Company, 1952), 284; also 112-113, 117-130, 146-150, 161-169, 285, and 288-317.
[158] Zachary, *Endless Frontier*, 78-79 and 107.

> a calculator (which is the usual way of solving such systems at present) by a factor of more than one hundred . . .
>
> In view of the very considerable value that the successful completion of this machine would have in scientific and technical applications would your organization be interested in advancing this grant?
>
> I have discussed these plans in some detail with Dr. Warren Weaver of the Rockefeller Foundation and I have reason to believe that he will be glad to discuss them with you. I have also had a brief conversation about these plans with Dr. Vannevar Bush who is, I believe, a member of your committee.[159]

Doubtless, Atanasoff had reason to claim the ABC, "should multiply the efforts of an expert computer with a calculator . . . by a factor of more than one hundred." In fact, no number of human computers could replace the ABC, just as a team of horses, no matter how large, cannot substitute for an internal combustion engine. The problem Atanasoff and Berry designed the ABC to solve involved more than extension of rote power but organizing and concentrating that power.

In any case, the president of the Research Corporation, Howard Poillon, replied in early August that its board of directors would not meet until late that year and could take no action until then.[160] The director for the CSAL, Irvin Stewart, had better news. He responded that, "it is quite possible that this Committee might be interested in a machine to do the type of things which you outline." Stewart added that he needed a detailed description of the ABC to give to computing experts to evaluate.[161] Weaver had already given the same advice.[162] Atanasoff therefore wrote a thirty-one-page manuscript (including two-page financial statement) entitled "Computing Machine for the Solution of large Systems of Linear Algebraic Equations" that explained the ABC. He mailed a copy each to Stewart and Weaver.[163] Stewart passed his copy on to Thornton Fry, of the BTL, and

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[159] John V. Atanasoff, copy of letter to Irgin (sic: Irvin) Stewart, Director, Committee on Scientific Aids to Learning, 10 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[160] Howard Poillon, President, Research Corporation, letter to John V. Atanasoff, 2 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[161] Irvin Stewart, Director, Committee on Scientific Aids to Learning, letter to John V. Atanasoff, 22 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[162] Warren Weaver, letter to John V. Atanasoff, 16 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[163] J. V. Atanasoff, copy of letter to Irvin Stewart, Director, Committee on Scientific Aids to Learning, 21 August 1940; J. V. Atanasoff, copy of letter to Warren Weaver, 22 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).

began making arrangements for Samuel Caldwell, at MIT, to travel to Ames to investigate.[164] Then, due to "an unexpected reduction in funds," the CSAL had to abandon consideration of the ABC.[165]

The two foundations had close communications, and no sooner did the CSAL drop the ABC, then Poillon asked Atanasoff if he wanted his application reopened.[166] It had been placed in inactive hold while the CSAL had the ABC under review. Atanasoff therefore sent Poillon a copy of his funding manuscript plus the news that progress had slowed considerably due to lack of funds, which in fact, were nearly exhausted.[167]

Fry then sent Poillon his copy of Atanasoff's funding manuscript and the information that he and Caldwell, "both believe the machine (the ABC) would be operative, that it would serve a very useful purpose, and neither of us could think of a more promising mechanism for carrying out this type of calculation." Moreover, Fry stated that his and Caldwell's only reservation was the small amount of money requested. They recommended funding the ABC even at twice the cost.[168] Caldwell did not go to Ames for the CSAL, but he did go in January 1941 for Project X. He subsequently reported confirmation of his favorable impression of the ABC obtained from reading Atanasoff's manuscript, and he exhorted the Research Corporation to grant Atanasoff the money requested.[169]

The board of directors for the Research Corporation met in December 1940, but finding the situation of the ABC more complex than anticipated, took no action.[170] Among those who meanwhile evaluated the project for the Research Corporation was Alan Hazeltine, Professor of Physical Mathematics at the Stevens Institute of Technology. He had invented the neutralized radio-frequency amplifier, making static-free radio possible and which became the basis for the Hazeltine

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[164] Irvin Stewart, Director, Committee on Scientific Aids to Learning, letter to John V. Atanasoff, 5 October 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[165] Irvin Stewart, Director, Committee on Scientific Aids to Learning, letter to John V. Atanasoff, 17 October 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[166] Howard Poillon, President, Research Corporation, letter to John V. Atanasoff, 23 October 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[167] J. V. Atanasoff, copies of letters to Howard A. Poillon, President, Research Corporation, 4 and 8 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[168] Thornton Fry, Mathematical Research Director, Bell Telephone Laboratories, copy of letter to Howard A. Poillon, President, Research Corporation, 12 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).
[169] S. H. Caldwell, Electrical Engineering Department, MIT, copy of letter to Howard A. Poillon, President, Research Corporation, 23 January 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).
[170] Howard Poillon (attributed), President, Research Corporation, copy of memorandum to (Carroll L.) Wilson, 23 December 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).

Corporation.[171] It then took several months for the directors to consider the ABC, apparently individually, and report back to Poillon, all to the affirmative.[172] A grant of $5,330 was not approved until late April 1941.[173] Moreover, per its policy, the Research Corporation gave the money to ISC, not directly to Atanasoff.[174] This became a point of contention because Atanasoff believed that ISC used its control to force him to sign a patent contract on terms he thought unfair. It is not clear how he kept the project going until July 1941, when he signed the contract, although circumstantial evidence suggests various departments may have provided small amounts of money. Starting early 1941, however, both Atanasoff and Berry turned the preponderance of their energies to Project X.[175]

With approval of Atanasoff's grant request, Fry wrote again to Poillon to say he "was very glad to learn" of it, and to add that the ABC "seems to me entirely realistic, and there is no doubt at all that the machine, when built, will find a wide field of usefulness."[176] Fry asked to keep a copy of the funding manuscript,[177] but Atanasoff had to refuse upon advice of his lawyer.[178] Stewart troubled to write to Atanasoff to express his satisfaction with the Research Corporation's decision.[179] Hazeltine, too, wrote to say that he found the ABC, "very interesting and was impressed by the possibility of extending it to automatic operation by determinantal methods" (as another way of solving linear algebraic equations).[180]

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[171] Editors of *Electronics*, *An Age of Innovation*, 171.
[172] Howard Poillon (attributed), letter to John V. Atanasoff, 20 February 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[173] Howard A. Poillon, President, Research Corporation, copy of letter to Treasurer, ISC, 30 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[174] Lloyd N. Scott, Secretary, Research Corporation, copy of letter to Charles E. Friley, President, ISC, 24 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[175] John V. Atanasoff, copy of letter to J. C. Morris, Director, Office of Scientific Personnel, Washington, D.C., 27 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 23).
[176] Thornton Fry, Mathematical Research Director, Bell Telephone Laboratories, copy of letter to Howard A. Poillon, President, Research Corporation, 27 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).
[177] Irvin Stewart, Director, Committee on Scientific Aids to Learning, letter to John V. Atanasoff, 14 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[178] John V. Atanasoff, copy of letter to Irwin (sic) Stewart, Director, Committee on Scientific Aids to Learning, 23 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 1).
[179] Stewart, letter to Atanasoff, 14 April 1941.
[180] Alan Hazeltine, Professor of Physical Mathematics, Stevens Institute of Technology, Hoboken, New Jersey, letter to J. V. Atanasoff, 2 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).

Historians of computers regard the general disapproval by scientists for the ENIAC as indicating that they were resistant to change, unable to accept the new technology. How then to explain the earlier enthusiasm, equally widespread, evident from experts who knew of the ABC? Admittedly, Aiken may not have been impressed. However, several years later, when asked to evaluate the UNIVAC proposal, Aiken recommended building instead computers more in line with the ABC.[181] This suggests that he came around to at least some of its merits. Bush, too, may not have appreciated the ABC, and he was an especially important figure. As head of the NDRC, Bush arguably became the most influential person in developing technologies in the United States, if not the world. What is interesting is that his most trusted advisors favored the ABC. These included Caldwell and Weaver. More important, it probably included Carroll L. Wilson. Wilson served as an official in the Research Corporation, which besides its philanthropic activities, handled patents for MIT and other universities.[182] Wilson came to know Bush well in that capacity, and then became his right hand man at the NDRC, to the point of being described as his "alter ego."[183] Certainly, Wilson must have approved funding the ABC. From the CSAL, Stewart became Bush's executive secretary. Jewett and Conant also became key aides at the NDRC. Thus, key people in the NDRD formerly had a hand in approving funding for the ABC. This suggests that perhaps Bush supported the ABC but had more pressing issues commanding his attention.

Atanasoff seemed oblivious to support for the ABC; rather, he complained of widespread skepticism. A favorite anecdote epitomizing his view involved fellow ISC physics professor, Lester Earls, whom Atanasoff alleged had once mocked, "That thing (the ABC) will never drive a streetcar." However, Atanasoff remembered unfavorable comments, for which we have his recorded recollections. He evidently forgot about positive reviews the ABC garnered, of which ample proof exists. For his part, Earls denied making the comment.[184] In any case, that so many authorities saw value in the ABC but not in the ENIAC suggests not reluctance to step into the future, but simply that they could tell the difference between a good invention and a bad one.

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[181] I. Bernard Cohen, *Howard Aiken: Portrait of a Computer Pioneer* (Cambridge, Massachusetts: MIT Press, 1999), 289-290.

[182] A. A. Potter, "Research and Invention in Engineering Colleges," *Science* 91, no. 2349 (5 January 1940), 4.

[183] Zachary, *Endless Frontier*, 122-123.

[184] Atanasoff, interview with Halladay, et al., 9 July 1968, 62; Atanasoff, interview with Kaplan, 10 August 1972, 17-18.

Atanasoff began efforts to patent the ABC concurrent with his search for funding. He asked A. E. Brandt to help, because he had better sources of information. The former ISC statistician had left Ames to take employment with the Department of Agriculture in Washington, D.C. Atanasoff specifically wanted an opinion on Albert Dieterich, who he used briefly on his tabulator attachment and ganged calculator proposals. If Dieterich should be thought unsuitable, then Atanasoff asked Brandt to obtain names of other patent lawyers.[185] Brandt talked the matter over with attorneys within the USDA. They knew nothing about Dieterich but supplied names of four other lawyers as possibilities.[186]

Atanasoff waited several months to contact the attorneys. All responded, and three thought they could help.[187] The fourth confessed that he was not qualified, but took it upon himself to discuss Atanasoff's situation with a Mr. Buttner, Principal Examiner for Division 23 of the U.S. Patent Office. Division 23 included calculating machines and would handle an application for the ABC. Atanasoff stipulated a lawyer with no connections with Remington Rand or IBM, and given that limitation, Buttner suggested Richard Trexler, of Cox, Moore & Olson in Chicago, whom he knew personally.[188] Trexler's experience included several years as an examiner in Division 23.[189] Atanasoff therefore retained Trexler.

As first order of business, Atanasoff and Trexler decided to hunt for patents that might relate to the ABC. Clerks had just begun going through Patent Office files, however, when Trexler halted work. Expecting a "relatively small job," he found the opposite. In a letter to Atanasoff, he explained: "This case is out of the ordinary because of the unusual number of patents owned by International Business Machines Corporation. Apparently this company has about as many patents as any company owns."[190] What they needed, Trexler suggested, was a way to narrow the search. Atanasoff eventually decided to go to Washington and conduct a search himself.

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185 Atanasoff, letter to Brandt, 5 January 1939 (sic: 1940).
186 A. E. Brandt, letter to J. V. Atanasoff, 12 January 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).
187 Robert H. Young, Patent Attorney, Washington, D.C., letter to John V. Atanasoff, 30 July 1940; T. Louis Wolk, Washington, D.C., letter to John V. Atanasoff, 31 July 1940; Aksel M. Pedersen, Attorney at Law, Washington, D.C., letter to John V. Atanasoff, 1 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
188 Martin T. Fisher, Attorney at Law, Washington, D.C., letter to John V. Atanasoff, 1 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
189 Richard R. Trexler, Cox, Moore & Olson, letter to John V. Atanasoff, 9 August 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
190 Richard R. Trexler, Cox, Moore & Olson, letters to John V. Atanasoff, 21 September 1940 and 26 September 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

In the meantime, Atanasoff, urged by Trexler, attempted to clarify his rights with ISC in the prosecution of a patent application.[191] ISC, like other schools in the 1920s and 1930s, had relatively little experience with patents. Patents traditionally had been left to inventors, who if they bothered to pursue them at universities and colleges, often simply turned them over to the public.[192] However, institutions of higher learning depended on support from industry and discovered that it sponsored research more willingly with patent policies in place. Industry preferred not to spend money on development of technologies without protection from pirating. Thus, universities and colleges began implementing policies largely to attract funding. Institutions did not expect to make money from the patents themselves, and policies normally applied only to patents resulting from research financed by the institution or in cooperation with outside agencies.[193]

ISC wrestled with the patent issue and eventually created the Iowa State College Research Foundation in 1938 as a nonprofit corporation legally separate from, but closely tied to, the college. Responsibilities included assisting faculty, staff, and student inventors obtain patents and ensuring availability of inventions by the public. Patents vested with the inventors, but ISC paid patenting and related expenses. In return, the school got a large portion of any ensuing income. However, in implementing its policy, ISC assumed that both expenses and commercial royalties would be low.[194]

Atanasoff formally notified R. E. Buchanan of his desire to patent the ABC in early November 1940. As Director of the Patent Committee, Buchanan had responsibility for making a preliminary decision on whether ISC should pursue a patent. He also served on the Research Foundation. These two duties covered only a small part of the remarkable man's official activities, however. A professor in bacteriology, he had a worldwide reputation in the field and headed the department at ISC. If not enough, he also served as Dean of the Graduate College. Atanasoff characterized Buchanan as "very shrewd," the man who "did everything at Iowa State College."[195]

Atanasoff sent Buchanan a copy of his funding manuscript to explain the device, and he stated in a cover letter that a patent should cover the machine and "certain other basis (sic)

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[191] John V. Atanasoff, copy of letter to Richard Trexler, Cox, Moore and Olson, 27 November 1940 (first of two letters that day). ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[192] Kevles, *The Physicists*, 268.
[193] Potter, "Research and Invention in Engineering Colleges," 3-7.
[194] Douglas Robillard, Jr., "A History of the Iowa State University Research Foundation, Inc., 1938-1988," unpublished paper, Iowa State University, Ames, Iowa, circa 1988, 1-18.
[195] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 24 July 1968, 32 and 37. ISU, Parks, "John Vincent Atanasoff Papers" (box 33, folder 1).

principles."[196] Buchanan recognized the groundbreaking nature of the ABC, and in fact, became so enthusiastic that Atanasoff wondered if perhaps he had not "over-sold" his computer.[197] Buchanan reported to the ISC Committee on Patents as follows:

> Doctor Atanasoff has rather independently made several discoveries which are not only useful in this machine (the ABC), but *may well find a very extensive use in design of cheaper and far more efficient computing machines of many types* (emphasis added). It is believed from every point of view to be desirable to hold and administer these patentable discoveries together. I would therefore specifically recommend that the patenting of the computing machine be handled in conformity with the standard practice of the Research Foundation, but that other matters and particularly the determination of the distribution of royalties and other income arising from application of the patent or patents to the general field of computing machines and similar devices be made a matter of direct negotiation and contract between the Foundation and Doctor Atanasoff.
>
> Inasmuch as this patent application is unusually technical and probably basic in a new field, it is urged that special care be used in selection of a patent attorney who is satisfactory to Doctor Atanasoff.[198]

The Patent Committee met at end of November and, following Buchanan's lead, recommended that the Research Foundation accept responsibility for patenting the ABC.[199]

Confident that the Foundation would choose to patent the ABC, Atanasoff had requested that it retain Trexler instead of another Chicago lawyer that normally got its business.[200] Quincy C. Ayres, Secretary of the Patent Committee and Executive Secretary of the Research Foundation, and Associate Professor of Agriculture Engineering, therefore went to Chicago in early December to meet him.[201] Trexler impressed Ayres, who advised that the Foundation accept Atanasoff's request. The ABC, he noted, was "away out of the class of anything we have heretofore dealt with." Moreover, "Dr. Atanasoff has informed himself to a surprising degree on patent law and patent procedure, particularly as applied to this invention, and it is believed he will be able to cooperate in such a way as to reduce to a minimum the time required of the patent attorney."[202] In short, Ayres recognized

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[196] J. V. Atanasoff, letter to R. E. Buchanan, Dean of Graduate College, 8 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[197] Atanasoff, copy of letter to Trexler, 27 November 1940 (first of two letters that day).
[198] R. E. Buchanan, Director, Committee on Patents, memorandum to Committee on Patents, 21 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[199] Q. C. Ayres, copy of memorandum entitled "Faculty Patent Committee," 30 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[200] Atanasoff, copy of letter to Trexler, 27 November 1940 (first of two letters that day).
[201] Richard Trexler, Cox, Moore & Olson, letter to John V. Atanasoff, 28 November 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[202] Quincy C. Ayres, memorandum to the Trustees of the Iowa State College Research Foundation, 13 December 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).

that the ABC patent application demanded a specialist. Atanasoff was best qualified to determine whom that should be and could assist with the patent or patents, thereby reducing total costs.

Not only could Atanasoff help with an application, but Ayres suggested he also render assistance coming to terms for a licensing agreement: "I think he can be trusted to do a good job of negotiating," noted Ayres.[203] As Ayres's comments implied, Atanasoff had a grasp of patent law among his areas of expertise. Atanasoff later referred to himself self-deprecatingly as a "2,000-hour patent lawyer," meaning he had spent that many hours "monkeying" with patents.[204] More important, Ayres's actions and comments implied deference to Atanasoff, the expectation that he lead the effort to patent the ABC. That was reasonable but led to disaster when first Ayres and then Atanasoff left, and the college itself got turned upside down, because of the war. No one else at ISC was prepared to keep the application on track.

That the Foundation ought to patent the ABC, Ayres whole-heartedly approved: "if it is as good as Dr. Atanasoff, Dr. Woodrow, Dean Buchanan and Mr. Trexler think it is (in which opinion I concur), it is something which will command very substantial sums for commercial control." Jay W. Woodrow was Chairman of the Physics Department. Given the unique and complex nature of the invention, Ayres and Buchanan now proposed to deviate from the standard contract.[205] Moreover, they recognized that the ABC resulted mostly from effort by Atanasoff on his own time,[206] and that its potential value went beyond what ISC could expect in return for the money it had given him.

The usual contract allowed an ISC inventor 15 percent of profits.[207] Ayres suggested instead one modeled on contracts used by the Research Corporation, "in which the Foundation receives forty percent of the net proceeds and the inventor receives sixty per cent after all expenses have been deducted. In our case Atanasoff agrees to an equal division of profits; forty-five per cent to himself and five per cent to a Mr. Berry who is now assisting in building *one type of a full-scale machine*" (emphasis added).[208] Atanasoff presumably agreed to a smaller share of profits because of the general expectation that the Foundation might incur unusually large patenting expenses.

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[203] Quincy C. Ayres (attributed), memorandum entitled "Computing Machine: John V. Atanasoff," circa 18 March 1941, 3. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[204] Atanasoff, interview with Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 11 July 1968, 34.
[205] Ayres, memorandum to the Trustees of the Iowa State College Research Foundation, 13 December 1940.
[206] Ayres, memorandum entitled "Computing Machine: John V. Atanasoff," circa 18 March 1941, 1.
[207] Q. C. Ayres, "Confidential Memorandum to Pres. Friley (President of ISC)," 25 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[208] Ayres, memorandum to the Trustees of the Iowa State College Research Foundation, 13 December 1940.

Meeting just after Christmas, the Board of Trustees for the Research Foundation considered the ABC but took no action, partly because of confusion over talk of an imminent commercial version different from the ABC. Ayres recorded in his minutes: "After due consideration of the very unusual nature and scope of this invention the group expressed great interest in the new principles but decided to withhold a decision on the matter pending an opportunity to inspect a commercial type machine in operation."[209] In fact, although Atanasoff recognized that all manner of computers could derive from the ABC, he had no immediate plans for another version.

To this point, matters with the Foundation had proceeded in a way entirely satisfactorily to Atanasoff.[210] He, Buchanan, and Ayres had in fact roughed out the initial terms. The situation changed quickly, unfortunately. Ayres prepared a proposal that the Trustees considered on March 22.[211] At least one, T. R. Agg, Dean of Engineering, objected to the unprecedented deviation from the standard contract, apparently believing that inventions made privately should be handled like any other.[212] The majority, led by Buchanan, stood their ground. They were especially concerned about Ayres's estimate that patenting costs on the ABC could "run from $500.00 up to well over a thousand," even with Atanasoff assisting.[213] Ayres therefore suggested equal division of profits and expenses, with the Foundation's share of expenses not to exceed five hundred dollars.[214]

The majority view prevailed, but Atanasoff strenuously objected when he saw the details of the resulting proposal.[215] As one problem, it did not specify that Berry get 10 percent of Atanasoff's

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209 Quincy C. Ayres, Secretary, Minutes of Special Meeting of Board of Trustees of ISC Research Foundation, 27 December 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
210 Atanasoff, copy of letter to Trexler, 27 November 1940 (first of two letters that day); John V. Atanasoff, copy of letter to Richard Trexler, 18 January 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
211 Ayres, memorandum entitled "Computing Machine: John V. Atanasoff," 18 March 1941; Quincy C. Ayres, Secretary-Manager, Minutes of Special Meeting of Board of Trustees of ISC Research Foundation, 22 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
212 Ayres, "Confidential Memorandum to Pres. Friley," 25 March 1941.
213 Ayres, memorandum entitled "Computing Machine: John V. Atanasoff," 18 March 1941, 1; Ayres, "Confidential Memorandum to Pres. Friley," 25 March 1941.
214 Ayres, Minutes of Special Meeting of Board of Trustees of ISC Research Foundation, 22 March 1941.
215 The contract terms resulting from the March 22 meeting of the Board of Trustees actually came from another of its members, C. Coykendall. Ayres put the terms in a short letter to Atanasoff as the contract. Coykendall believed a more detailed contract might become necessary later for commercialization. C. Coykendall, Engineer, Estimates and Contracts, Iowa State Highway Commission, letter to John V. Atanasoff, 3 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 26).

share of pre-expense income.[216] Atanasoff demanded the contract include that stipulation. More important, Atanasoff wanted the contract to read: "the costs of securing a patent be divided evenly *without restriction* (emphasis added)."[217] As another point, Atanasoff apparently desired say over how ISC distributed income among departments, so that those that had rendered aid for the ABC might be reimbursed.[218]

Atanasoff became embittered over subsequent negotiations and blamed Charles Friley, president of ISC, for using his control of the money from the Research Corporation to force him to sign an agreement he otherwise would not have.[219] Such evidence as exists suggests that Friley followed the recommendation of the Foundation, however.[220] For example, apparently no one but Atanasoff saw advantage to including Berry in the contract. Even Trexler took that view.[221] Rather, he and the Foundation believed that division of profits between the two inventors could be better handled by separate agreement. Atanasoff later drew up the indenture with Berry for that purpose.

More contentious was the issue of a ceiling on expenditures. The Research Foundation strongly believed it needed to be cautious about incurring expenses. As of June 1941 and since its creation in 1938, it had handled twenty-one active or pending patents, including the ABC. It had received total income of $10,596, yielding a profit of $5,980.[222] That made ISC a profit leader among colleges or universities, since few made any money at all from patents.[223] A patent at ISC for blue cheese gave most profits over the years but also greatest headaches due to numerous patent infringements.[224] Thus, the Foundation gave primary consideration to avoiding large expenditures.

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[216] Quincy C. Ayres, Secretary-Manager, ISC Research Foundation, letter to John V. Atanasoff, 24 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[217] J. V. Atanasoff, letter to Charles E. Friley, President, ISC, 15 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[218] Harold V. Gaskill, Dean of Science, letter to Wallace E. Barron, 24 June 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[219] However, Atanasoff admitted that he had little direct knowledge of the role Friley played in the affair. John V. Atanasoff and Alice Atanasoff, letter to Clark Mollenhoff, 7 December 1986. ISU, Parks, "Clark Mollenhoff Papers, 1968-1990" (box 1, folder 20).
[220] Charles E. Friley, President, ISC, letter to T. R. Agg, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[221] Richard R. Trexler, Cox, Moore & Olson, letter to John V. Atanasoff, 19 December 1940, 2. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[222] Wallace E. Barron, "Iowa State College Research Foundation Annual Report," 7 June 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[223] Potter, "Research and Invention in Engineering Colleges," 6.
[224] Robillard, "A History of the Iowa State University Research Foundation," 24-27; Wallace E. Barron, "Iowa State College Research Foundation Annual Report," 6 June 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).

The Foundation agreed with Ayres in anticipating that the ABC might "command very substantial sums for commercial control," but saw that not as potential for millions or billions, as might be supposed today, but rather, thousands of dollars. Atanasoff admitted years later that he had expected the patent to sell for $25,000 to $50,000.[225] The Foundation presumably thought it might get less. However, it is noteworthy that while no one saw commercial possibilities for computers based on the example of the ENIAC, even novices recognized such potential deriving from the ABC.

After several months of haggling, the Foundation raised its expense ceiling to $750. Atanasoff grudgingly signed the slightly modified agreement on 5 July 1941,[226] and the Research Corporation grant finally became available to him. Things might have gone better if Ayres had stayed, because Atanasoff had much respect for him, as he also had for Buchanan. However, after the March meeting, Ayres left for duty in the Naval Reserve as a Lieutenant Commander in the Civil Engineer Corps for the duration of the "present national emergency." Wallace E. Barron, Director of Alumni Affairs, assumed administrative responsibilities for the Foundation in his absence.[227] Barron admitted knowing, "almost nothing about this patent business."[228]

Atanasoff decided to make another trip east over Christmas break 1940 but neglected to tell his wife. Earls, a neighbor, took him aside and admonished that he could not leave his unsuspecting family at Christmas.[229] Atanasoff had not thought about it, but reminded, he and his wife loaded their three children into the family car and left town on Friday the 20th. They drove to New York, visited relatives, and arrived in New York City on or before the 23rd. Atanasoff attended to business while his family saw the sights.

He met with Ehret and J. B. Hayward of IBM, hoping, first, to come to an agreement on the ABC and, second, to finally clinch employment, but nothing on either materialized. IBM continued to be interested in the ABC, but with Atanasoff refusing to sign a disclosure agreement, and in fact unable to pending action by the Research Foundation, Ehret had his hands tied.[230] Hayward sounded

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[225] John V. Atanasoff, quoted in Clark Mollenhoff, "Court: Computer Iowan's Idea," *Des Moines Register*, 27 January 1974, 8A.
[226] Wallace E. Barron, ISC Research Foundation, agreement letter to John V. Atanasoff, 5 July 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[227] Ayres, "Minutes of Special Meeting of Board of Trustees of ISC Research Foundation," 22 March 1941.
[228] Barron, "Iowa State College Research Foundation Annual Report," 7 June 1941, 1.
[229] Gather, interview with Paul Mobley, 1 July 1998.
[230] Clement Ehret, Director Market Research, IBM, transcription of letter to J. B. Bayard (Hayward?), Patent Development Supervisor, IBM, 18 December 1940. Charles Babbage Institute, Honeywell

more optimistic about prospects for employment but led Atanasoff to believe that IBM's "unsettled foreign situation" prevented it from adding an "academic" at that time.[231]

Incidentally, Atanasoff claimed he had repeatedly tried over the years to interest IBM in the ABC but failed.[232] On the contrary, Ehret continually pressed him to patent the ABC so IBM could inspect it.[233] As his last words to Atanasoff in late 1942, Ehret said he was "keeping the matter in our active files awaiting further advice from you."[234]

Also in New York City, Atanasoff tried to meet with Poillon on his pending grant application but apparently missed connections. Finally, Atanasoff met with Weaver, out of the hospital and distributing national defense projects.[235] The NDRC had already approved well over one hundred by then, a year before the Japanese attack on Pearl Harbor.[236] Atanasoff had been offering ideas, and in particular, believed the method to direct antiaircraft fire could be simplified. Weaver therefore tentatively assigned him Project X.[237]

The Atanasoff family spent Christmas in a New York City hotel (which the children thoroughly enjoyed).[238] They drove to Philadelphia the next day so Atanasoff could attend a joint conference of the American Association for the Advancement of Science (AAAS) and American Physical Society. While there, he sat in a lecture on analysis of weather data using an electrical harmonic analyzer, a type of analog computer. Mauchly presented the lecture and had built the analyzer based on one at MIT. Son of a physicist for the Carnegie Institution in Washington, D.C., Mauchly had studied electrical engineering before switching to physics and obtaining a Ph.D. degree from John Hopkins University. He taught undergraduate physics courses at Ursinus College in Collegeville, near Philadelphia, but curiously, typically described himself as either a research

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Collection (box 3, folder 2); Clement Ehret, Director Market Research, IBM, letter to John V. Atanasoff, 16 January 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

[231] John V. Atanasoff, copy of letter to J. B. Hayward, IBM, 22 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

[232] Atanasoff, quoted in Mollenhoff, "Court," 8A.

[233] For example, see Clement Ehret, Director Market Research, IBM, letter to J. V. Atanasoff, 13 August 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

[234] Clement Ehret, Director Market Research, IBM, letter to J. V. Atanasoff, 21 December 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 2).

[235] Atanasoff, interview with Halladay, et al., 10 July 1968, 58 and 64; "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968; M. Tamme, Secretary to Mr. Poillon, President, Research Corporation, letter to John V. Atanasoff, 16 December 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

[236] Kevles, *The Physicists*, 298.

[237] Atanasoff, interviews with Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 11 July 1968, 41-43, and 23 July 1968, 3; Atanasoff, interview with Kaplan, 23 August 1972, 110-111.

[238] Gather, interview with Paul Mobley, 1 July 1998.

engineer or statistical geophysicist.[239] What he said about himself when he met Atanasoff is not known, but Atanasoff made a point of talking with him after the lecture. Atanasoff claimed he did so only because he liked to meet people at conferences and actually had little interest in the analyzer or weather data. In any case, the two men had a discussion in which Atanasoff provided a vague description of the ABC. Upon parting, he invited Mauchly to Ames to see his computer.

After several days in Philadelphia, the Atanasoff family drove to Washington, D.C., and was joined by Berry, who arrived by bus.[240] Atanasoff and Berry spent the week of the New Year going through files in the Patent Office with assistance from its personnel. Trexler provided instructions but otherwise did not help.[241] Atanasoff believed they obtained a good understanding of the ABC compared to the "past art." He did not find it original in every detail; in particular, patents had been granted on somewhat similar ideas to his on recording and reading of binary numbers using high-voltage arcs. On the whole, Atanasoff noted happily: "our basic notion of computing machine is quite in the clear, and this was confirmed by the examiners."[242]

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[239] Burks and Burks, *The First Electronic Computer*, 74-75; *Sperry Rand v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823 and 15,824, "Deposition of John William Mauchly," 12, 17, and 22-23. ISU, Parks, "John Vincent Atanasoff Papers" (box 19, folder 3).
[240] Atanasoff, interviews with Halladay, et al., 10 July 1968, 20-21, 28-29, and 63-64.
[241] Richard Trexler, Cox, Moore & Olson, "Memorandum to Mr. Atanasoff," 20 December 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[242] John V. Atanasoff, copy of letter to Richard Trexler, Cox, Moore & Olson, 13 January 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22); Clifford Edward Berry, "Design of Electrical Data Recording and Reading Mechanism," unpublished M.S. thesis, Iowa State College, Ames, Iowa, 1941, 4 and 31.

CHAPTER 5. MORE ON THE ABC

January 1941 proved especially eventful for the ABC. Immediately after Atanasoff returned home together with his family and Berry from Washington, D.C., Samuel Caldwell visited at the request of Warren Weaver. The trip was related to Project X, and it is likely that he specifically investigated use of the ABC in Project X.[1] Weaver himself went to Ames on the 12th,[2] and later in the month assigned Caldwell temporary responsibility for "steering Atanasoff."[3] Caldwell then made an apparently unsolicited recommendation to the Research Corporation that it fund completion of the ABC, which it finally did that spring.

January also saw first publicity of the ABC. On the 15th, the *Des Moines Tribune* ran a short article accompanied by a photograph under the caption "Machine Remembers." The photograph showed Berry holding a large component, heavy with vacuum tubes, mistakenly identified as a memory but actually control circuits. The article, entitled "Computing Device," and including the inevitable comparison to the human brain, read as follows:

> An electrical computing machine said here to operate more like the human brain than any other such machine known to exist is being built by Dr. John V. Atanasoff, Iowa State college (sic) physics professor.
>
> The machine will contain more than 300 vacuum tubes and will be used to compute complicated algebraic equations, Dr. Atanasoff said. It will occupy about as much space as a large office desk.
>
> The instrument will be entirely electrical, and will be used in research experiments.
>
> Dr. Atanasoff said he has been working on the machine several years, and probably will finish it in about a year.[4]

Finally, Mauchly initiated a series of correspondences with Atanasoff that culminated in his driving to Iowa in June to examine the ABC, and then continued for some months afterward. The letters between the two men deserve quoting at length in chronological order. Mauchly's first letter,

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[1] *Honeywell Inc. vs. Sperry Rand Corporation and Illinois Scientific Developments, Inc.*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Transcript of Proceedings," 1,914-1,916; 1,926; and 2,115. ISU, Parks, "John Vincent Atanasoff Papers" (box 43, folder 1 through box 44, folder 2); "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968. ISU, Parks, "John Vincent Atanasoff Papers" (box 27, folder 5).

[2] J. V. Atanasoff, copy of letter to Norman A. Clark, 7 January 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 9, folder 7).

[3] S. H. Caldwell, National Defense Research Committee, copy of memorandum to Warren Weaver, Rockefeller Foundation, 29 January 1941. Charles Babbage Institute, Honeywell Collection (box 3, folder 4).

[4] *Honeywell*, "Transcript of Proceedings," 1,856-1,860; Clifford E. Berry, copy of letter to R. K. Richards, 12 July 1963. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 23).

on January 19, several weeks after meeting Atanasoff, read as follows:

> I am wondering how your plans with regard to computing devices are working out. Need I say again that I await with some suspense the time when you will be able to let me have more information? How the recording-end functions is the biggest puzzle, I guess—450 digits at less than $2 per digit sounds next to impossible, and yet that is what I understand you to say, approximately.
>
> Your suggestion about visiting Iowa seemed rather fantastic when first made, but the idea grows on me. I've gone so far as to note that our Spring Recess is March 21 to 31, whereas the meetings in Washington are about May 1.
>
> The financial questions involved in a long trip haven't been solved, though. If you aren't too busy, perhaps you can drop a few hints as to your progress.[5]

Mauchly knew little about the ABC until he went to Ames. Atanasoff had told Mauchly no more than he said to anyone he did not know well. The computer had nevertheless gripped the interest of Mauchly; so much so, he contemplated making the trip west as early as March. Driving part way across the country is not notable now, but this was the Depression, and Mauchly worried about expenses. Finally, the comment about "450 digits at less than $2 per digit" has unclear origins. Atanasoff may have told him that total cost of the ABC might run about $2 per bit of storage capacity. That turned out a fair estimate if based on the combined 3,000 binary digit capacity of the two memory drums, but Atanasoff typically said that the ABC had 450 digits of memory, giving a figure based on the capacity of a single drum in its decimal digits equivalent.[6] In court, however, he testified that $2 per digit was the marginal cost of adding memory to the ABC.[7]

Delighted at Mauchly's interest, Atanasoff responded almost immediately, as follows:

> Your letter came as a pleasant surprise. I intended to write to you as soon as the effect of the new term on my activities had worn away.
>
> As you know we have been in active construction on the computing machine for more than a year, and now our plans have assumed rather definite form, and progress is good without too much attention on my part. I am expecting shortly to hear whether or not I will receive a grant-in-aid from an outside source to help in completing the machine. All in all progress is very satisfactory to me, and I expect that our plans will commence to mature in about a year.
>
> . . . Just after my return we had a visit from Dr. S. H. Caldwell of M. I. T. who gave me a rather complete picture of calculating machine activities in the country. His visit gave me the urge to attempt the construction of a differential analyser on a dime store basis. I believe this attempt could be rather successful, and it is something I have laid away for future activity when my work gives out.

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5 John W. Mauchly, letter to John V. Atanasoff, 19 January 1941, quoted in *Honeywell*, "Transcript of Proceedings," 2,104-2,105.

6 See for example, ISC news release "Biggest, Fastest Calculator Built by ISC Physicist," 7 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 5).

7 *Honeywell*, "Transcript of Proceedings," 1,973.

By all means arrange to pay us a visit in Ames during your spring recess if this is possible. Our spring recess is from March 19 to March 24, and I can think of many things that I would like to talk to you about. This list includes statistical Fourier analysis, resistance harmonic analysers, computing machines of all kinds, and I suspect there are plenty of other things. I will be glad to have you as my guest while you are in Ames. As an additional inducement I will explain the two dollar per digit business.[8]

Atanasoff's idea about a differential analyzer on a "dime store basis" involved building an ingenious but simple attachment to the ABC. The attachment, actually an analog-to-digital converter, was to function something like input boards on a differential analyzer, except that tracing a curve would produce a digital signal that could be integrated numerically by the ABC.[9] Put simply, the converter effectively divided the area under a curve into exceeding narrow rectangular blocks whose areas could be calculated easily and summed by the ABC to give an approximate total area. The attachment would not make the ABC a general-purpose computer, however, but significantly extend its capabilities and do it quite cheaply.

Mauchly responded about a month later as follows:

Your invitation and the promised explanation are indeed powerful inducements, and I hope that I shall be able to take advantage of them.

Somewhere—was it in Nature? —I saw an article on differential analyzers which included a picture of an analyzer constructed largely from Meccano parts. I think the "dime-store" analyzer ought to be successful. If it did no more, it would justify itself in merely aiding students to understand the process of mechanical solution of differential equations. Incidentally, do you consider the usual d.analyzer an "analogue" machine? If so, how about a polar planimeter?

My crew of N.Y.A. people has been augmented, but perhaps not for the better. The new members are fit only for adding machine work, and even then can't get the same total more than two out of three times (so it seems!).

We recently had to take the back off of the harmonic analyzer for a few minor adjustments. Some of the IRC 50,000 ohm resistors had aged to the point where they were not within one percent. that we desire. Someday we'll put wire-wounds in and forget them, I hope.

So far we have turned out about 1400 harmonic analyses—each one for eight Fourier coefficients. At 3 minutes per, this has taken just 70 hours. The tabular method that we would otherwise use takes about 5 times as long (but does yield more accurate values, which we do not need for this work). Hence we figure that we have saved 280 hours . . . which is

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[8] John V. Atanasoff, copy of letter to John W. Mauchly, 23 January 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[9] John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 11 July 1968, 11-18. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 2).

> about the amount of time it took to design and build the device. It wouldn't take that long to build another, of course, especially if one purchased precision wire-wound resistors to assemble.
>
> Here's hoping that you have made progress in Iowa, and that I'll get out to see it all.[10]

Not surprisingly, Mauchly misapprehended what Atanasoff meant by a differential analyzer on a dime store basis. Differential analyzer implied analog, although few people yet grasped the difference between analog and digital. That Mauchly did not is clear by his asking Atanasoff if he considered a "d.analyzer (differential analyzer) an 'analogue' machine?" It was, of course, as was a polar planimeter, a device something like a wheel-and-disc integrator and used for finding areas on maps and scaled drawings.[11] Thus, Mauchly naturally assumed Atanasoff had in mind building a miniature analyzer using kits available in toy stores. Meccano parts in Great Britain were roughly like Erector sets in the United States, and British physicist Douglas Hartree had constructed a functioning differential analyzer with them.

The "N.Y.A. people" were youths hired under a New Deal make-work program, the National Youth Administration. Mauchly had a dozen or so helping with analysis of weather data.[12] Specifically, his research involved investigating the relationship between activities on the sun and weather on earth. Finally, it is worth noting that Mauchly's harmonic analyzer was electrical, but not electronic, and obviously troublesome.

In reply, Atanasoff continued to encourage Mauchly to visit, as follows:

> By all means pay us a visit if you can arrange it. Just drop me a line, letting me know when you will get here, so that I will be sure to be on hand. At present I am planning to attend the Washington meetings at the end of April.
>
> Several of the projects which I told you about are progressing satisfactorily. Pieces for the computing machine are coming off the production line, and I have developed a theory of how graininess in photographic material should be described, and have also devised and constructed a machine which directly makes estimates of graininess according to these principles. We will try to have something here to interest you when you arrive, if nothing more than a speech which you make.[13]

In his initial letter on January 19, Mauchly mentioned Washington meetings around May 1 that he evidently planned to attend. The reason for those meetings is not known, but the meetings in

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[10] John W. Mauchly, letter to John V. Atanasoff, 24 February 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[11] Atanasoff, interview with Halladay, et al., 11 July 1968, 1-3.

[12] Alice R. Burks and Arthur W. Burks, *The First Electronic Computer: The Atanasoff Story* (Ann Arbor, Michigan: University of Michigan Press, 1988), 75 and 124.

[13] J. V. Atanasoff, copy of letter to John W. Mauchly, 7 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

late April for Atanasoff were an orientation to Project X, and in particular, included a demonstration of antiaircraft fire at Ft. Monroe, Virginia. He and others with projects in fire control attended the live-fire exercise. Taking advantage of the trip, Atanasoff also met with Walter G. Cady, an authority in crystal physics. His comment about graininess in photographic material involved another of his research areas, which he must have broached with Mauchly in their introductory conversation in Philadelphia. Mauchly had interest because Atanasoff described granularity with a time-series analysis something like he needed for his study of barometric pressures.[14]

Mauchly decided at the last moment not to drive to Iowa at end of March. He sent Atanasoff a telegram to tell him of his change of plans[15] and followed with a letter:

> Here is the letter which I said would "follow," and by this time there should be no question about it—no matter what theory of relativity you use, this letter should arrive after the night message.
>
> I was sorry not to get out there, but work that I wanted to get done here was piling up, a prospective passenger who might have shared the expense didn't think he could leave just now, and some one who used to live in Iowa painted an unattractive picture of the weather possibilities for driving at this time of year.
>
> Now I am trying to arrange a passenger for June—or won't you be around Ames during that time of year? I hope to see you in Washington when you come to the meetings, and you can let me know then how things would shape up for a June visit.
>
> I haven't been able to do more than just paper-work for a computing machine here, so I haven't yet found out how practical my ideas are. We've been very busy running barometric pressures through the harmonic analyzer in order to get some more information on the 12-hour tidal oscillation.
>
> It's good to hear that your "production line" is producing. Is there any chance that you can now disclose more information?[16]

Important here is the evidence that Mauchly had been thinking about building a "computing machine." Actually, first evidence comes in a letter he wrote to a colleague in November 1940,[17] before he met Atanasoff, in fact. One proximate inspiration may have been his witness of a demonstration of the Complex Number Computer that September at Dartmouth. However, first evidence of him seriously considering requirements for a calculator came on 1 January 1941, about a

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[14] Atanasoff, interview with Halladay, et al., 11 July 1968, 45-46 and 49; *Honeywell*, "Transcript of Proceedings," 2,126; Walter G. Cady, letter to John V. Atanasoff, 19 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 7, folder 2).

[15] J. W. Mauchly, Western Union telegram to A. V. Atansoff (sic), 22 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[16] John W. Mauchly, letter to J. V. Atanasoff, 31 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[17] John W. Mauchly, letter to H. Helm Clayton, 15 November 1940. Quoted in John W. Mauchly, "Mauchly: Unpublished Remarks," *Annals of the History of Computing* 4, no. 3 (July 1982), 248.

week after meeting Atanasoff. Notes he jotted down that day included "At. Machin" and "150 tubes," evidently indicating that he had understood the ABC used about 150 vacuum tubes.[18]

Atanasoff delayed almost a month before responding, involved as he was in wrangling with the ISC Research Foundation, but more urgently steeped in Project X. His reply to Mauchly said little except that he hoped they could meet back east.[19] However, they missed connections in Washington, and pressing business forced Atanasoff to abandon any attempt to meet. Back in Iowa, Atanasoff wrote Mauchly a letter that included the following excerpt:

> It was one of my keen disappointments not to be able to see you while in the East. I planned to stop at Collegeville on my way from Washington to New York, but a sudden telephone call necessitated my making a continuous trip. Several matters connected with the defense project which I have undertaken made my visit in the East a very strenuous one. I am looking forward to seeing you in some way or another in the very near future.[20]

Mauchly, in turn, replied in part as follows:

> It was a disappointment to me, too, not to get in touch with you while in Washington. . . .
>
> Well, anyway, there is more than a little prospect of my making the trip, starting from here about the tenth of June. I have a passenger who will very likely pay for the gas, and that will help.
>
> From your letters I have gathered that your national defense work is unconnected with the computing machine. This puzzles me, for as I understand it, rapid computation devices are involved in N.D. In a recent talk with Travis, of the E.E. School at U. of Pa. I asked him about this, and the matter seemed the same way to him. But if Caldwell has looked over your plans (I think you said that he was out there) and hasn't seen any N.D. possibilities, I suppose that that means your computer is not considered adaptable to fire control devices, or that they have something even better. Travis (who goes into active duty with Navy this week) pointed out the advantages of lightness and mass-production for electronic computing methods, but said that when he was consulting with General Electric over plans for the G.E. differential integraph they figured it would take about one-half million dollars to the job electronically, and they would only spend 1/5 of that, so they built the mechanical type with Polaroid torque-amplifiers.[21]

Having decided against a trip to ISC in March, Mauchly now determined to go in June. Especially intriguing in this letter is how he inferred so much about Atanasoff's national defense (N.D.) work; it is unlikely that Atanasoff had told him. Perhaps Mauchly knew enough about

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[18] *Honeywell*, "Transcript of Proceedings," 11,844-11,856. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 8).

[19] John V. Atanasoff, copy of letter to J. W. Mauchly, 22 April 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[20] J. V. Atanasoff, copy of letter to John W. Mauchly, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[21] J. W. Mauchly, letter to J. V. Atanasoff, 27 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

Caldwell's activities to guess. More likely, he got his information from Irven Travis, who, as noted, left that week for the Navy. Not coincidentally, Travis was yet another computing expert pulled into antiaircraft fire-control studies. However, the American scientific community was relatively small in the early 1940s and Atanasoff fairly well known, so Mauchly might have learned of Atanasoff's activities from a number of sources.

As for Travis, he had supervised the building of two differential analyzers modeled on Vannevar Bush's, one for the Army and another for the University of Pennsylvania, where he taught electrical engineering. Mauchly used the word integraph here to mean differential analyzer, as did others. In 1939 and 1940, after building the analyzers, Travis prepared two proposals for the General Electric Corporation. The first suggested the possibility of an electronic differential analyzer, something like the Rockefeller Analyzer. The second recommendation was reminiscent of one of Atanasoff's ideas: a digital computer consisting of ganged calculators. Travis further proposed that the calculators, perhaps electronic, be organized roughly like components of a differential analyzer but with the calculators replacing integrators. He worried that mechanical calculators might not stand up well but did not give electronic ones serious consideration. Partly for that reason, apparently, GE did not act on Travis's reports. However, Mauchly's letter suggests that GE decided that such a complex but limited calculating machine could not be justified at that cost, just as Bush decided not to build the Arithmetical Machine until it could be simplified. As Mauchly reported, GE built a differential analyzer more of the old-style instead.

Which proposal Mauchly meant in his letter is unclear, but regardless, Travis had come close to proposing an ENIAC, that is, an electronic digital differential analyzer with multipliers, accumulators, and interconnecting components. According to Travis, Mauchly had visited him at the University of Pennsylvania, "from time to time and we had numerous chats" on "automatic computation." Thus, it is likely that the essential concept of the ENIAC derived from Travis. To strengthen the connection, Travis had been a favorite instructor of Eckert.[22]

The original name for the ENIAC was the Electronic Diff. Analyzer, a deliberate allusion to the Differential Analyzer. However, Diff. stood not for differential, but for difference, that is, for the numerical method of finite differences for solving differential equations. The April 1943 proposal to the Army for the ENIAC, written by Mauchly, Eckert, and John G. Brainerd, a director of research at

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[22] Irven Travis quoted in Burks and Burks, *The First Electronic Computer*, 186; also 126-127, 182-188, and 190-191.

the University of Pennsylvania and an authority on vacuum tubes and analog computers,[23] stated that, "electronic difference analyzers have been considered for different applications in at least two previous cases, but have not been developed and used."[24] One of Travis's proposals probably was one case and the ABC with integrating attachment the other.[25] In testimony, however, Herman Goldstine recalled Mauchly telling him that the two machines were Atanasoff's and one at MIT, presumably the Rockefeller Analyzer.[26] In any case, between the ABC and either Travis's or MIT's advanced computers, perhaps even the Arithmetical Machine, Mauchly had the basis for the ENIAC. However, it must be noted that the ENIAC solved problems fully digitally, and thus differently than the ABC and integrating attachment.

Atanasoff was eager to accommodate Mauchly no matter when he could make it to Ames and responded at the end of May as follows:

> I think that it is an excellent idea for you to come west during the month of June or any other time for that matter . . . We have plenty of room and will be delighted to have you stay with us while here.
>
> As you may surmise, I am somewhat out of the beaten track of computing machine gossip, and so I am always interested in any details you can give me. The figures on the electronic differential integraph seem absolutely startling. During Dr. Caldwell's last visit here, I suddenly obtained an idea as to how the computing machine which we are building can be converted into an integraph. Its action would be analogous to numerical integration and not like that of the Bush Integraph which is, of course, an analogue machine, but it would be very rapid, and the steps in the numerical integration could be made arbitrarily small. It should therefore equal the Bush machine in speed and exell (sic) it in accuracy.
>
> Progress on the construction of this machine is excellent in spite of the amount of time that defense work is taking, and I am still in a high state of enthusiasm about its ultimate success. I hope to see you within two or three weeks.[27]

Caldwell had been back at ISC on March 24.[28] However, Atanasoff's sudden idea on converting the ABC into an integraph is presumably the same one he had in early January. The $500,000 for an electronic differential analyzer shocked Atanasoff, but the ENIAC cost that and more. Perhaps it was not coincidental that at this time GE inquired about the ABC. That March, a

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23 *Honeywell*, "Transcript of Proceedings," 12,277-12,278; Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, New Jersey: Princeton University Press, 1973), 133; John G. Brainerd, "Genesis of the ENIAC," *Technology and Culture* 17, no. 3 (July 1976), 483-486.

24 Excerpt quoted in Burks and Burks, *The First Electronic Computer*, 110-111; also 186-190.

25 Burks and Burks, *The First Electronic Computer*, 111 and 186-192.

26 "Testimony of Goldstine before Halladay," 871-872. ISU, Parks, "John Vincent Atanasoff Papers" (box 28, folder 3).

27 J. V. Atanasoff, copy of letter to J. W. Mauchly, 31 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

28 "Atanasoff Chronology Event List (Master Copy)," compiled by Dorsey, Marquart, Windhorst, West & Halladay, 16 September 1968.

GE representative had written to Atanasoff as follows: "it is possible that the General Electric Company would have an interest in acquiring the right to make and use the machine or in cooperating with the college in its further development."[29] Atanasoff responded to GE much like he did to all the corporations interested in the ABC: He thanked them but refused to sign any agreement until assured of patent rights.[30]

Mauchly, now about ready to travel to Ames, replied to Atanasoff as follows:

> At present I can't say just when I shall arrive, but it (is) fairly certain when I shall start out, anyway. We wind up our year here with a faculty meeting Tuesday, June 10, in the evening. Then we (a friend and his mother are riding with me to Iowa to visit some of their relatives) will leave early Wednesday morning. I am not one of those 24-hour drivers, so I will not try to equal your record—there is no doubt but that it take us two days.
>
> And just where in Iowa my friends want to go I haven't found out yet. But I might spend Friday the thirteenth at the Univ. of Iowa Colloquium. That would mean that you might expect to hear from me that Friday or Saturday, or perhaps find me on your doorstep at some late or early hour.
>
> Enclosed is an announcement that you might find interesting as an example of what goes on around here. I suppose there are similar enterprises all over the country. Pennsylvania is going in for a defense training course for high school graduates, too. I thought I might be teaching in that program, but they haven't notified me of any need for my abilities—and they have hired one of our chemistry men. One hears, all around, that physicists are in so much demand, but it doesn't seem so in the neighborhood of Collegeville.
>
> I'll finish this letter when I see you.[31]

Note the comment about Atanasoff's "record," alluding to his notorious high-speed driving. Note, too, that despite the practically insatiable demand for physicists in defense research, Mauchly, actively hunting, was having trouble finding a new position.

Mauchly gave Atanasoff no further warning before arriving at his home on Friday evening, June 13.[32] Moreover, he brought his six-year old son, telling his hosts that he had decided to give his wife a rest. Caught by surprise, Lura Atanasoff rushed to prepare the guest bedroom. Not only had she not expected the boy, she had not expected the father. For all his entreaties to Mauchly to be his guest in his home, Atanasoff had not told his wife, or at least had not kept her informed.

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[29] H. B. Marvin, General Engineering Laboratory, General Electric Company, letter to John V. Atanasoff, 11 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 12).
[30] J. V. Atanasoff, copy of letter to H. B. Marvin, General Engineering Laboratory, General Electric Company, 20 March 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 12).
[31] John W. Mauchly, letter to J. V. Atanasoff, 7 June 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).
[32] Atanasoff, interview with Halladay, et al., 11 July 1968, 19-20.

Worse, Mauchly behaved inexcusably. He left his son with Lura Atanasoff without a word, expecting her to take care of him, and largely ignored them both through his stay while she cooked meals for everyone. Mrs. Atanasoff loved guests and socializing, including the family parties held regularly by the faculty of the Physics Department, but she came to resent Mauchly and recalled his visit all too well when called to testify. She described him as "one of those superior professors," "always talking," but rarely in "polite conversation," and with a habit of saying condescendingly, "Now, that's interesting."[33]

Perhaps Mauchly's deplorable deportment came partly from disappointment. The ABC was approaching completion when he saw it—Atanasoff thought several more months ought to do[34]—so Mauchly had opportunity to give it a thorough assessment. In initial deposing, however, he downplayed his visit, saying that he spent only thirty minutes or so at the ABC, that Atanasoff had been reluctant to speak of it, and anyway, there was not much to it. He could muster no recollection of Berry.[35] In testimony, he emphasized that the ABC simply had not met his expectations. He hinted rather that he found it primitive. As far as he took interest in the computer, he claimed, he magnanimously offered suggestions on improvements.[36]

Unfortunately for Mauchly, witnesses reported a different story. He "expressed joy" over it, countered Atanasoff, who recalled spending twenty-five or thirty hours in discussions on the ABC with him. Moreover, according to Atanasoff, all conversations had been open; he and Berry answered any question Mauchly asked.[37] Likewise, Lura Atanasoff, divorced in 1949, remembered Mauchly in constant conversation with her ex-husband on the ABC when at home. Specifically, she recalled him asking questions, but he seemed to have trouble understanding explanations.[38]

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[33] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823-15,824, "Deposition of Lura Atanasoff," 5 December 1967, 9-14. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 8, folder "Dep-Lura"); Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone with Paul Mobley, 1 July 1998.

[34] J. V. Atanasoff, copy of letter to R. M. Bowie, Hygrade Sylvania Corporation, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5); J. V. Atanasoff, New Market, Maryland, interview with H. Tropp, 24 May 1972, 113-115. Smithsonian.

[35] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823-15,824, "Deposition of John W. Mauchly," 88 and 140. ISU, Parks, "John Vincent Atanasoff Papers" (box 19).

[36] *Honeywell*, "Transcript of Proceedings," 11,829-11,830 and 12,161-12,169.

[37] *Honeywell*, "Transcript of Proceedings," 2,136 and 2,166-2,167.

[38] *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Lura Atanasoff," 27-28. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 8, folder "Dep-Lura").

Others also refuted Mauchly. Sam Legvold, a graduate student in physics, had primary responsibility for Project X, like Berry for the ABC. Work areas for the projects were adjacent in the basement of the Physics Building, and Legvold and Berry were friends, so he was introduced to Mauchly and talked with him. Legvold remembered Mauchly spending considerable time over several days with Berry at the ABC, and even recalled him in shirtsleeves helping. He "was delighted with what he saw," according to Legvold. Furthermore, conversations were "no holds barred," completely "free and open."[39]

Even Berry provided testimony in a letter he wrote in 1963, not long before he died. In the letter to R. K. Richards, who had graduated from ISC and vaguely remembered the ABC and wanted to know more for a book on digital computers he was researching,[40] Berry added the note: "An interesting sidelight is that in 1940 or 1941 we had a visit from Dr. John Mauchly who spent a week learning all of the details of our computer and the philosophy of its design. He was the only person outside of the Research Corporation and the patent counsel who was given this opportunity."[41]

Particularly important testimony concerned Mauchly's reading of the ABC funding manuscript. As mentioned, the manuscript gave an overall description of the computer. Computing experts including Caldwell and Thornton Fry had been deeply impressed by it. Atanasoff said that he let Mauchly borrow a copy, and it served to facilitate discussions. He thought those discussions had covered the entire manuscript. Moreover, Mauchly asked to keep the copy, but Atanasoff refused, as he had Fry, allowing him access only in Ames.[42] Atanasoff did give Mauchly plenty of paper, however, and allowed him to take whatever notes he wished.[43] It is conceivable that Mauchly copied the entire manuscript by hand.

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[39] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823-15,824, "Deposition of Sam Legvold," 6 December 1967, 22-25; C. G. Call, memo entitled "Legvold Interview," 21 September 1967, 9-10. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 8, folders "Sam Legvold Deposition" and "Call Memos").

[40] Clark R. Mollenhoff, *Atanasoff: Forgotten Father of the Computer* (Ames, Iowa: Iowa State University Press, 1988), 93; R. K. Richards, copy of unsigned letter to Clifford Berry, 12 March 1963. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 1, folder "R. K. Richards"); Richards credited the ABC as the ancestor of all electronic digital systems. See, R. K. Richards, *Electronic Digital Systems* (New York: John Wiley and Sons, 1966), 3-4.

[41] Clifford E. Berry, Director of Engineering, Consolidated Electrodynamics Corporation, copy of letter to R. K. Richards, 22 March 1963. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 1, folder "R. K. Richards").

[42] *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Deposition of Dr. John V. Atanasoff," 765. ISU, Parks, "John Vincent Atanasoff Papers" (box 30); *Honeywell*, "Transcript of Proceedings," 2,133-2,138.

[43] John Vincent Atanasoff, "Advent of Electronic Digital Computing," in *Annals of the History of Computing* 6, no. 3 (July 1984), 255.

For his part, Mauchly barely remembered the manuscript. He said he thought it rather inadequate and had not bothered with it much. As he phrased it with a haughty air: "there wasn't any great reward for me to try to memorize the details." Oddly, he remembered any number of details on occasion. For example, he rather off-handedly recalled discussing magnetic storage devices, a topic mentioned in the manuscript. He finally confessed that he may have asked to keep a copy, but that was only because he had a habit of collecting "sales literature" and such.[44]

It is a wonder that Atanasoff, otherwise cautious, trusted Mauchly. Certainly his family did not. His wife, suspicious, warned him not to talk too much.[45] Daughter Joanne, about ten-years old then, remembered Mauchly intently studying the manuscript and taking notes. She grew alarmed at the way he "pumped" her father for further information.[46]

In defense of Atanasoff, Mauchly could be charming and had a way of winning sympathy. Furthermore, if Atanasoff acted naïvely, it was partly out of virtue. A rigorously honorable man himself, he assumed the same of others, especially scientists. Moreover, not to be underestimated as a factor was the isolation that Atanasoff felt. If those feelings seem slightly unreasonable in light of full evidence, they were nonetheless real and often intense. He believed that only his graduate students appreciated the ABC, but he had found at last in Mauchly a kindred spirit. He put his guard down because he desperately wanted a peer who shared his enthusiasm.[47]

It is unknown how long Mauchly intended to stay in Ames, but he and his son cut short their visit and left on Wednesday, June 18, after receiving a message from his wife of a pending job interview.[48] Several days later, he sent a letter to Atanasoff, as follows:

> The trip back here was uneventful, except for the fact that I was carrying on a mental debate with myself on the question of whether to teach at Hazelton, or to learn something of (sic) U. of Pa. My natural avarice for knowledge vied with that for money, and won out, so after obtaining assurance . . . that some one else to take the Hazelton work, I dropped that and prepared to become a student again.
>
> I drove to Southbridge, Mass., Friday evening, and looked through the American Optical plant on Saturday morning. They seemed quite serious in their intentions to me, but no decision is to be made for several weeks.
>
> On the way back east a lot of ideas came barging into my consciousness, but I haven't had time to sift them or organize them. They were on the subject of computing devices, of course. If any look promising, you may hear more later.

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[44] *Honeywell*, "Transcript of Proceedings," 11,833-11,835 and 12,161-12,167.
[45] *Sperry Rand*, "Deposition of Lura Atanasoff," 12 and 17.
[46] Gather, interview with Mobley, 1 July 1998.
[47] John V. Atanasoff, transcript of interview with Henry S. Tropp, Smithsonian Institution, 24 April 1972, 14-15; J. V. Atanasoff, transcript of interview with B. Kaplan, Smithsonian Institution, 17 July 1972, 14-15. Smithsonian.
[48] *Honeywell*, "Transcript of Proceedings," 12,210-12,211.

> I do hope that your amplifier problem has been licked by some adequate design. The tubes that I ordered two weeks ago aren't here yet, so I couldn't try anything here even if I had the time.
>
> I forgot to ask what happens to Cliff Berry after he gets a master's degree—does he stay on for Ph.D. work?
>
> Please give the enclosed note to your wife. We enjoyed our trip very much, and hope you can stop here some time.[49]

Mauchly's "mental debate" involved whether to teach a summer defense course to high school graduates or take such a course himself at the University of Pennsylvania. As it happened, he elected to become a student, and in fact, met Eckert during the course on electronics in which Eckert served as lab instructor. That Mauchly felt the need to take the course hints that he did not yet have the skills to have done much in electronic computers. Adding to his mental turmoil, Mauchly admitted having "a lot of ideas" on computing devices, suggesting that the ABC had indeed stimulated his thinking and gave impetus to his decision to enroll in the electronics course.

Finally, although Atanasoff could not recall the amplifier problem during testimony, a contemporary document points to instability of "contact potential difference between (vacuum tube) grid and cathode." Atanasoff asked Hygrade Sylvania Corporation for assistance, and he subsequently took its advice on how to correct the problem in vacuum tubes in the ABC and, probably, Project X.[50]

Further evidence that the ABC had impressed Mauchly far more than he later admitted comes from a letter he wrote to an acquaintance on 28 June 1941, not long after arriving home in Pennsylvania. The letter read in part as follows:

> Immediately after commencement here, I went out to Iowa State University (sic) to see the computing device which a friend of mine is constructing there. His machine, now nearing completion, is electronic in operation, and will solve within a very few minutes any system of linear equations involving no more than thirty variables. It can be adapted to do the job of the Bush differential analyzer more rapidly that the Bush machine does, and it costs a lot less.
>
> My own computing devices use a different principle, more likely to fit small computing jobs.
>
> While at Iowa, I talked on the construction of harmonic analyzers. But I haven't done anything about the 27-ordinate cost-estimate as yet.
>
> All of my time since coming back from Iowa has been taken up with an Emergency Defense Training Course at the Univ. of Pa. I had a chance to teach for the summer in a defense course given to high school graduates, but turned that down in order to become a student myself. I am working in electrical engineering and electronics. Whether or not I am

[49] J. W. Mauchly, letter to J. V. (Atanasoff), 22 June 1941, quoted in *Honeywell*, "Transcript of Proceedings," 2,169-2,170.

[50] J. V. Atanasoff, copy of letter to G. D. O'Neill, Hygrade Sylvania Corporation, 26 July 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).

> given a defense job involving electronics later on, the training will be helpful in connection with electronic computing devices.
>
> I haven't had any chance to work on weather problems recently. I did hear Rossby talk at Iowa City—concerning the training of students for meteorology, etc. Let's hope your own work is getting along well.[51]

Note that, contrary to his trial testimony, Mauchly originally considered the ABC an electronic computer with significant capabilities. Moreover, this letter makes clear that whatever digital computing device he had considered to this point was smaller and based on a different principle. Mauchly never disclosed the principle, but presumably it involved flip-flop counting circuits.

Within two months of visiting Atanasoff, Mauchly produced his first documentation of preliminary effort towards realizing an electronic digital calculating device. Included in these various notes and schematics made during August and September 1941 are references to Atanasoff. For example, in a document entitled "Notes on Electrical Calculating Devices," dated August 1941, Mauchly included such information as: "computing machines may be conveniently classified as either 'analog' or 'impulse' types." In a footnote, he added that he was "indebted to Dr. J. V. Atanasoff" for that understanding. Mauchly went on to add:

> For speedy (and noiseless) operation, vacuum tubes and associated circuits are the obvious answer. There are no essential difficulties in designing V.T. apparatus to do the job of ordinary mechanical calculators—but after taking care of stability, freedom from error, ease of servicing, etc., one might conceivably wind up with a design too costly to build. But economically feasible designs are possible. At present it may not be possible to build a commercial competitor for the desk-type mechanical computer, but larger machines for more involved, more lengthy, or more specialized jobs are practical.[52]

This summary accurately described the problem of the times: People saw the possibility of an electronic digital calculator but not how to make one of reasonable capabilities and cost. Atanasoff and Berry discovered the keys as embodied by the ABC, and then the computers of today. Eckert and Mauchly rather inexplicably regressed to old arts, and in the ENIAC built a computer too expensive and limited for anyone but government.

In testimony, Mauchly proudly called attention to a schematic attached to "Notes on Electrical Calculating Devices," that showed, he claimed, "a layout for something which could almost be the present day electronic desk calculators that are being manufactured and sold all over the

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[51] John W. Mauchly, copy of letter to (H. Helm) Clayton, 28 June 1941. Charles Babbage Institute, Honeywell Collection (box 3, folder 7).

[52] John W. Mauchly, "Notes on Electrical Calculating Devices," August 1941. Charles Babbage Institute, Honeywell Collection (box 3, folder 7).

country now." However, he pointedly failed to mention that in the upper left corner of the schematic were the underlined initials "JVA," certainly referring to Atanasoff. Moreover, the desktop machine was the most advanced calculator he could show that he had considered to that time, and it only in rudimentary form.[53]

Also in August, Mauchly applied to the University of Pennsylvania for a position with its Moore School of Electrical Engineering.[54] The school needed faculty but did not want to hire him. Even so, it could find no one else and gave him a job.[55]

Mauchly then wrote to Atanasoff, providing best evidence of how enthusiastic he had become over the ABC and suggesting how meager his own efforts must have been. The letter, on 30 September 1941, read as follows:

> This is to let you know that I still have the same living quarters, but a different job. During the summer I looked around a bit while sounding out the Ursinus people as to promotions and assistance; I finally gave up the idea of taking an industrial job (or a navy job) and stayed in the ranks of teaching.
>
> The Moore School of Electrical Engineering is what I have joined up with, and they have me teaching circuit theory and measurements and machinery—but only 11 hours a week instead of the 33 that Ursinus had developed into.
>
> As time goes on, I expect to get a first-hand knowledge of the operation of the differential analyzer—I have already spent a bit of time watching the process of setting up and operating the thing—and with more such background I hope I can outdo the analyzer electronically.
>
> A number of different ideas have come to me recently anant (sic) computing circuits—some of which are more or less hybrids, combining your methods with other things, and some of which are nothing like your machine. The question in my mind is this: Is there any objection, from your point of view, to my building some sort of computer which incorporates some of the features of your machine? For the time being, of course, I shall be lucky to find time and material to do more than merely make exploratory tests of some of my different ideas, with the hope of getting something very speedy, not too costly, etc.
>
> Ultimately a second question might come up, of course, and that is, in the event that your present design were to hold the field against all challengers, and I got the Moore School interested in having something of the sort, would the way be open for us to build an "Atanasoff Calculator" (à la Bush analyzer) here?
>
> I am occupying the office of Travis, the man who designed the analyzer here (duplicated at Aberdeen); I think I told you that he is now in the Navy, so I have no opportunity of benefiting by his rich experience.

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[53] *Honeywell*, "Transcript of Proceedings," 12,232-12,234; attachment to Mauchly, "Notes on Electrical Calculating Devices," August 1941.

[54] John W. Mauchly, copy of letter to Harold Pender, Dean, Moore School of Electrical Engineering, University of Pennsylvania, 6 August 1941. Charles Babbage Institute, Honeywell Collection (box 3, folder 8).

[55] Scott McCartney, *ENIAC: The Triumphs and Tragedies of the World's First Computer* (New York: Walker and Company, 1999), 48-49.

> I hope your defense efforts have been successful, but not so time-consuming as to stop progress on the computer. When you are East, arrange to see us. Perhaps you would like to look over the diff. analyzer, etc.
>
> Convey my best regards to your family, and Cliff Berry and all the gang.[56]

First, note Mauchly's unabated interest in the differential analyzer that he hopes to "outdo" electronically. Moreover, based on what he had learned in Ames, he was thinking of new methods of computing, "hybrids," incorporating Atanasoff's ideas with others, including presumably counting circuits and analog methods. He asked to use some of those concepts, perhaps even to build an "'Atanasoff Calculator' (à la Bush analyzer)," that is, an ABC with integrating attachment. All this points to the ENIAC. Another hint is the mention of Travis, who in fact, had already imparted at least the rudiments of his "rich experience" to Mauchly.

Atanasoff responded quickly to Mauchly's letter, no doubt alarmed at his request to use the ideas he had been keeping under guard. The letter, dated 7 October 1941, read as follows:

> I am delighted to hear that you are teaching in the Department of Electrical Engineering at the University of Pennsylvania, and I will be sure to get in touch with you the next time I come east which should be in the very near future. At that time we can discuss our mutual interest in calculators.
>
> Our attorney has emphasized the need of being careful about the dissemination of information about our device until a patent application is filed. This should not require too long, and, of course, I have no qualms about having informed you about our device, but it does require that we refrain from making public any details for the time being. It is, as a matter of fact, preventing me from making an invited address to the American Statistical Association.
>
> We greatly enjoyed your visit last spring and hope that it can be repeated in the not too distant future.[57]

Atanasoff made another trip east during October, and wanted to see Mauchly, but could not stop in Philadelphia. With misgivings, he took an hour at MIT to look over the Rockefeller Analyzer, nearing completion. It impressed him as a "most pretentious structure." Otherwise, his time was filled with matters related to Project X. He wrote to Mauchly upon his return to Ames that the trip had been "among the most strenuous (times) in my life."[58] That letter was their last communication until Mauchly went to see Atanasoff at the NOL early in 1943, before beginning the ENIAC. In the meantime, the ABC had to be set completely aside to give priority to projects for the national defense, beginning with Project X.

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[56] John W. Mauchly, letter to J. V. (Atanasoff), 30 September 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[57] John V. Atanasoff, copy of letter to John W. Mauchly, 7 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

[58] John V. Atanasoff, copy of letter to John W. Mauchly, 30 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 14).

The purpose of Project X was to develop mechanisms to aid human operators aim antiaircraft guns. It and similar projects had urgent status because, at start of World War II, airplanes had become a dominant weapon with capabilities that had greatly outpaced countermeasures. Antiaircraft gun crews attempted to shoot down airplanes much like hunters kill ducks on the wing by leading with their fire. The task was more difficult for aircraft because the guns were much heavier, but to the point of Project X, because warplanes flew significantly higher and faster than birds. It took five to thirty seconds for a projectile to travel the distance to target, by which time the airplane had flown a long way. Compounding the problem, the pilot meanwhile likely made evasive maneuvers, including changing directions and speeds. Firing a shell close to target and having it explode on time to inflict significant damage was therefore largely luck. In late 1940 over Britain, for example, some 10,000 rounds of 3-inch antiaircraft fire had to be expended for every German plane downed.[59]

Even if ineffectual, antiaircraft equipment was sophisticated and complicated. A typical system for the heavier antiaircraft guns included a tracking device consisting of a constant velocity mechanism that drove a sighting telescope and measuring instruments. An observer tried to keep the crosshairs of the telescope on the target by turning cranks to change the driving velocity and adjust for target position. It took two or three members of an antiaircraft gun crew to determine the altitude, azimuth (direction), and range of a target.[60] Information from the tracking device automatically fed into another device, the predictor, which calculated an estimate of the future position of the target when a shell might intersect. The prediction went to a ballistics computer that incorporated a pre-calculated ballistics table and controlled the setting of the shell fuse and aiming of the gun.[61]

Project X consisted largely of studies under two consecutive contracts generally dealing with aircraft tracking and flight-path prediction. Weaver probably assigned the project to Atanasoff because of his combined practical and theoretical skills, because of the project's high priority, and because it could be handled at ISC. Particularly important was Atanasoff's expertise in linear operators, such as functionals, and especially Taylor expansions and similar mathematical techniques, typically used to predict, or as mathematicians said, extrapolate, the future positions of aircraft based

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[59] Warren Weaver, *Scene of Change: A Lifetime in American Science* (New York City: Charles Scribner's Sons, 1970), 79; *Honeywell*, "Transcript of Proceedings," 2,115.

[60] John V. Atanasoff and Harold V. Gaskill, et al., "A Study of Antiaircraft Tracking: Final Report under Contract OEM sr 165," 2. National Archives; J. V. Atanasoff, transcript of interview with H. Tropp, Smithsonian Institute, 7 June 1972, 195-202. Smithsonian.

[61] John V. Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDC-143," 2-5. National Archives.

on current positions, velocities, and accelerations.[62] Since actions of a pilot under fire tended to be purposely erratic, extrapolation was the weakest link in antiaircraft fire control.

Project X became effective on 1 March 1941, although the contract did not become official until May 28. It called for "preliminary studies relating to a fire control device," allowed for $5,000 of expenditures (including a windfall 50 percent overhead to ISC), and was to terminate with a final report by 1 September 1941.[63] In his proposal submitted in February, Atanasoff noted that a number of formulae had potential, but he suggested that one utilizing the first three terms of a Taylor expansion should have advantages in mechanization of the extrapolation process and ease of use.[64] Atanasoff subsequently conducted various studies, issued four associated reports,[65] designed a predictor, and came in under budget,[66] although several days late with the final report.[67] He then took a rare and much needed vacation to visit his parents in Florida before the ISC fall term began.[68]

Even before expiration of the original contract, however, the NDRC, or actually a newly created superior organization, the Office of Scientific Research and Development (OSRD), expanded the project and issued another contract to continue work until 30 June 1942. The NDRC deemed that the predicting mechanism Atanasoff proposed had no "important advantage," although it contained "clever and original ideas." It nonetheless decided that certain associated studies "yielded indications of an important nature" and wanted to pursue them further. It first approved $18,000 additional money, but then decided to have Atanasoff build a prototype predictor after all and changed the value of the contract to $22,500.[69] In December, the OSRD issued a supplemental agreement to increase

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[62] J. V. Atanasoff, New Market, Maryland, interview with B. Kaplan, 23 August 1972, 116-121. Smithsonian.

[63] National Defense Research Committee, Contract No. NDCrc-143 with Iowa State College, 28 May 1941. National Archives.

[64] John V. Atanasoff, "Observing-Directing Mechanism for Antiaircraft Artillery," circa 10 February 1941, 1 and 6. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 7).

[65] Office of Scientific Research and Development, "Certification RE Final Report Requirements: Contract No. NDCrc-143 and NDC-165," 20 April 1945. National Archives.

[66] Office of Scientific Research and Development, "Liquidation Record: NDCrc-143," 19 March 1943 (last entry on 10 June 1947 indicated an ending balance of $834.00). National Archives.

[67] John V. Atanasoff, copy of letter to Duncan Stewart, Barber-Coleman Company, 8 September 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).

[68] John V. Atanasoff, copy of letter to William G. Parmenter, 30 September 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).

[69] Office of Scientific Research and Development, memorandum entitled "Project Recommended for Appropriation No. 12B: Extension and Supplementation of Project No. 12, Section D-2—Fire Control: Study of Tracking and Predicting Mechanisms," circa June-July 1941; Office of Scientific Research and Development, memorandum entitled "Project #21: Recommendation of Extension of Project #12 by Section D-2 (Fire Control)," 7 July 1941; Vannevar Bush, Director, OSRD, copy of letter to C. E. Friley, President, ISC, 28 July 1941. National Archives.

the amount to $40,500 to include yet more studies.[70] It had actually budgeted $75,000 for work by Atanasoff at ISC.[71]

The studies at ISC involved human subjects, since an observer formed a critical link as a "servo-mechanism" in the overall "psycho-mechanical complex" of fire control.[72] Atanasoff had assistance from Harold V. Gaskill, Dean of Science and Professor of Psychology, and any student lingering around the Physics Department likely got conscripted as a test subject. As a basic matter, Atanasoff needed the studies to design a tracker-predictor for accurate and easy usage. Other studies attempted to define desirable qualifications and training for observers. For example, one study tested how well people retained training. It turned out that with "over-learning," that is, thorough training, they lost little skill.[73] Other tests compared the performance of women and men and were conducted anticipating that women might serve as observers. Women did not do as well, but Atanasoff believed there was a bias in the tests and concluded that there was probably no actual difference in abilities.[74]

Like many scientists thrust into defense research, Atanasoff found the secrecy a burden. It caused a "strange atmosphere," giving "rise to some irritation irrespective of the patriotism of the individuals," and made it difficult to stay "in an enthusiastic state of mind without contacts with others working in the same field." In short, it added to the isolation that Atanasoff felt. He wished for more discussions with others doing similar studies, and although there were many, all were far away. Thus, he valued the periodic visits made by Weaver and his lieutenants, Caldwell and Fry, who served mainly as information middlemen.[75]

Actually, visits by the men were something of a mixed blessing. Caldwell came most often, but according to Atanasoff, he would, "bemoan the fact that he was in a country where culture was not as rampant as it is in Boston."[76] When weary of the complaints, and to "demonstrate the cultural

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[70] Office of Scientific Research and Development, "Contract No. OEMsr-165 Supplement No. 1 with Iowa State College," 9 December 1941. National Archives.
[71] Atanasoff, interview with Halladay, et al., 11 July 1968, 48.
[72] Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDC-143," 1; Atanasoff and Gaskill, et al., "A Study of Antiaircraft Tracking: Final Report under Contract OEM sr 165," 2.
[73] Samuel W. Fernberger, Technical Aide, D-2, OSRD, letter to John V. Atanasoff, 21 November 1942. For further details, see "Supplementary Report on Tracking II." ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folders 6 and 7).
[74] Atanasoff and Gaskill, et al., "A Study of Antiaircraft Tracking: Final Report under Contract OEM sr 165," 48.
[75] Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDC-143," 1-2; Atanasoff, interview with Kaplan, 23 August 1972, 109-110; John V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 11 May 1972, 155-157. Smithsonian.
[76] Atanasoff, interview with Kaplan, 23 August 1972, 111-112.

atmosphere of Ames," Atanasoff hosted a "musical" at his house and arranged for a mathematics professor who was a "fiddler" to play. Shortly after the music began, however, Caldwell excused himself and disappeared for most of the performance. Atanasoff did not ordinarily like classical music but enjoyed it that night.

At least Caldwell behaved himself; Fry and Weaver did not always. Fry discovered how part of the alarm system protecting Project X worked and deliberately set it off as a boyish prank. That caused Atanasoff no shortage of trouble with security officials. Another time, Fry and Weaver insisted that Atanasoff accompany them out on the town. As they made their way from bar to bar, Fry and Weaver announced in each that Atanasoff was a ISC professor, knowing that ISC officials frowned on drinking by faculty, even in their homes.[77]

When Atanasoff left ISC in September 1942, Project X had been substantially completed, but Legvold and Gaskill stayed behind and mopped up paperwork and assorted details. Atanasoff issued two major reports under the second contract,[78] which came in far under budget.[79] He believed he had taken visual tracking, or aided laying as it was called,[80] about as far as it could go but could do little to eliminate extrapolation errors. In any case, aided laying constituted a stopgap effort until better technologies could be perfected. By mid-1942, the BTL developed the analog M-9 electrical director, which proved deadly to aircraft when used with radar and proximity fuses.[81] Atanasoff nonetheless felt his research merited greater consideration for use in the war.[82]

On the other hand, Weaver testified in *Honeywell v. Sperry Rand* that Project X had turned out "a great disappointment due to Atanasoff's bad behavior." He did not give substantiating evidence and there is nothing to support his allegation. Moreover, he made other, clearly spurious, charges. For instance, he maintained that as a student Atanasoff had been "near the end of the line," when in fact, he had been outstanding, and Weaver himself had given him an A grade in at least one class. As for the grant application Atanasoff submitted to the Rockefeller Foundation for the ABC,

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[77] Atanasoff, interview with Halladay, et al., 11 July 1968, 24, 42-43, and 57-58.
[78] *Honeywell*, "Transcript of Proceedings," 2,733-2,734; Office of Scientific Research and Development, "Certification RE Final Report Requirements," 20 April 1945.
[79] The contract, OEMsr-165, closed at $28,168.63. C. G. Cruikshank, Budget and Finance Officer, OSRD, copy of letter to Harold V. Gaskill, Director (sic: Dean of Science), ISC, 22 April 1947. National Archives.
[80] Atanasoff, interview with Tropp, 7 June 1972, 199-202; Atanasoff, interview with Kaplan, 16 August 1972, 4.
[81] Weaver, *Scene of Change*, 81-86.
[82] Atanasoff, interview with Halladay, et al., 11 July 1968, 53 and 59; John V. Atanasoff, copy of letter to Colonel Harold E. Pride, 29 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 1).

Warren said he did not remember it but the, "odds were that he would have thrown Atanasoff's paper in the waste basket as soon as he opened the envelope." Furthermore, according to Weaver, Atanasoff got the NDRC contracts only because the government funded about any research with even "slim prospects" for success. When lawyers suggested that what he termed "imaginative" and "erratic" behavior in Atanasoff might also indicate brilliance, Weaver would have none of that. The essence of his testimony was that he considered Atanasoff, "not awfully able and not awfully sound."[83]

It is unknown what specifically caused Weaver to bear such deep hatred for Atanasoff for so many years. When faced with Weaver's testimony, Atanasoff voiced surprise. He had thought their relations fine. Whatever the cause, Atanasoff did not deny some responsibility for the hard feelings. In particular, he recalled a time during Project X when Weaver sat in a classroom "sobbing," because "no one felt his ideas important."[84] Rather cryptically, Atanasoff explained: "One of my faults is that I have an absolutely independent mind and it is not easily controlled by others, and I gathered at that time that this was the cause of that."[85] In short, he must have been ignoring Weaver's suggestions. It is well to remember that both Weaver and Atanasoff were under intense pressure during the war.

As a side note, Norbert Wiener at MIT did similar studies in antiaircraft fire control as Atanasoff.[86] Wiener also worked for Weaver, and in fact, Wiener and Atanasoff consulted together intensively during Atanasoff's trips back east. Atanasoff thought Wiener eccentric but "a very, very able man."[87] Even so, Wiener had no better luck developing an effective aircraft flight predicting mechanism, but the experience in dealing with control mechanisms and statistical treatment of data, for both machines and humans, led him after the war to found cybernetics, described as the study of communication and control theory.[88] To a smaller extent, Atanasoff interacted with Claude Shannon, who as noted, was another key figure in launching communications theory with Weaver.[89]

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[83] *Honeywell v. Sperry Rand*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, "Summary of Testimony of Dr. Warren Weaver," 6 March 1972, 6-8. ISU, Parks, "Henry L. Hanson Papers" (box 5, folder 2).

[84] Atanasoff, "Advent of Electronic Digital Computing," 272.

[85] *Honeywell*, "Transcript of Proceedings," 2,738-2,739.

[86] Norbert Wiener, *I am a Mathematician: The Later Life of a Prodigy* (Garden City, New York: Doubleday, 1956), 240-255.

[87] Atanasoff, interview with Halladay, et al., 11 July 1968, 47; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 23 July 1968, 55, 6-8, 23, and 24-25. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 7).

[88] Norbert Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine* (New York: John Wiley & Sons, 1948), 10-34; *Honeywell*, "Transcript of Proceedings," 2,115.

[89] John V. Atanasoff, copy of letter to Harold W. Anderson, 30 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 7, folder 2).

As another note, it may seem curious that Atanasoff did not incorporate the ABC into military activities, such as Project X. After all, as Atanasoff stated the obvious, a fire-control device could be "regarded as a combined measuring instrument and computing machine."[90] Actually, months before Project X, Atanasoff wrote to Dunham Jackson, mathematics professor at the University of Minnesota and a rare authority on approximation techniques, and member of the War Preparedness Committee, about the ABC. Atanasoff closed by alluding to an earlier conversation between the two men, and continued: "I quite agree that it is likely that other applications of mathematics will likely be of greater importance (in a war) than the application of mathematics to ballistics."[91] The implication was that he recognized that the ABC, or machines based on its principles, had applications for defense.

However, when Atanasoff and other computing experts began military projects, fire control took priority over other applications of mathematics, including calculating ballistics tables. Despite what might be assumed today, analog computers were superior to digital ones for antiaircraft fire control, at least then. Atanasoff discussed both categories with Caldwell and Weaver before dispassionately recommending that the NDRC continue to use analog machines.[92] On the other hand, Travis proposed digital computers. Weaver had to refuse under the circumstances.[93] RCA, Eastman Kodak, and NCR did investigate electronic digital fire-control directors later, although none of the projects were completed during the war.[94] Even if finished, however, it is doubtful that any could have served better than analog devices.

Digital computers had accuracy as their main advantage. However, inaccuracies of computation for fire control were insignificant compared to errors in following, and much worse, extrapolation. Furthermore, although digital is associated with speed, analog machines came in great variety and some, particularly special-purpose and electrical ones, could operate as fast. Indeed, they had the potential to perform essentially in "real time," something digital computers could not do until the Whirlwind computer completed in the early 1950s. Whirlwind actually began, in part, as a project to build an analog computer, but as a digital machine was not suited for field duty because of its size and complexity. Moreover, an analog computer had a major advantage in that signals from

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90 Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDCrc-143," 6.

91 J. V. Atanasoff, copy of letter to Dunham Jackson, 1 July 1940. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 20).

92 Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDCrc-143," 6-8.

93 Burks and Burks, *The First Electronic Computer*, 185-186.

94 *Honeywell*, "Summary of Testimony of Dr. Warren Weaver," 6 March 1972, 5.

measuring instruments could be fed in directly without intermediate processing to digitize, or as Atanasoff said, "arithmetize" them. All this was true for both the calculations of extrapolations and ballistics in fire control.[95] Analog computers served adequately and were simpler and more rugged than digital ones.[96]

Berry made rapid advancements on the ABC for the first year or so, but with money about exhausted by Christmas 1940 and with the start of Project X soon thereafter, progress slowed considerably. Atanasoff wrote to Richard Trexler in May 1941, after beginning Project X but while waiting for the Research Corporation grant to be released to him: "I find it rather hard to express myself about the delays which our project has incurred, in a way that is both lucid and within the formal bounds of written correspondence."[97] Optimistic nevertheless, he wrote to R. M. Bowie that same day: "You will be interested to know that our computing machine project has made great strides. . . I have had two very excellent men assisting me in the construction, and we expect to have the entire structure operating during the summer or soon thereafter."[98] Besides Berry, the "two very excellent men" probably included a student in mechanical engineering, Gert H. Weiseman.[99] Robert Mather went to work for Berry about this time,[100] and Atanasoff came to regard him as excellent.[101] With such help, Atanasoff anticipated completion of the ABC within three or four months.

A year later, however, he was still estimating that completion might take another two or three months. In May 1942, as a guest on an ISC radio program, Berry reported that his and Atanasoff's involvement in defense work had greatly hindered the ABC, but they hoped to see its completion

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[95] Atanasoff, et al., "Elements of Anti-Aircraft Fire Control: Final Report Under Contract NDCrc-143," 7; Atanasoff, interview with Halladay, et al., 11 July 1968, 46-47 and 54.
[96] J. V. Atanasoff, New Market, Maryland, transcript of interview with Henry S. Tropp, 17 April 1972, 30-31; Atanasoff, interview with Tropp, 24 May 1972, 118-119; Atanasoff, interview with Tropp, 7 June 1972, 196 and 198-199; Atanasoff, interview with Kaplan, 23 August 1972, 116-118. Smithsonian.
[97] J. V. Atanasoff, copy of letter to Richard Trexler, Cox, Moore and Olson, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[98] J. V. Atanasoff, copy of letter to R. M. Bowie, Hygrade Sylvania Corporation, 21 May 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 23, folder 5).
[99] Atanasoff, interview with Kaplan, 23 August 1972, 2-3; Atanasoff, interview with Henry Halladay, et al., 11 July 1968, 31-32; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 22 July 1968, 57. ISU, Parks, "John Vincent Atanasoff Papers" (box 32, folder 6).
[100] Robert Mather, Oakland, California, tape-recorded interview made over the telephone with Paul Mobley, 2 March 1998.
[101] John V. Atanasoff, transcript of interview with Bonnie Kaplan, Smithsonian Institution, 10 August 1972, 50. Smithsonian.

during the summer.[102] Atanasoff, in equal measures exasperated and confident, likewise confided to Howard Poillon that progress on the ABC had been, "greatly retarded by the attention which my laboratory is giving to certain investigations in connection with national defense." Otherwise, "the machine should have been in operation before this time."[103] That same day in April, he made a formal report to the Research Corporation as follows:

> In spite of the conditions which have tended to draw off technical and scientific ability at all levels into war activities, excellent progress has been made during the past year in the construction of the computing machine for which you so generously made a grant-in-aid. This activity has consisted principally in the actual construction of parts, since a large portion of the design work was done before this period. However, considerable work has been done in the detail design of the actual working parts of the apparatus. The machine is largely completed. The main part left unfinished consists in certain details of the apparatus by which numbers are put into and extracted from the machine. In the course of this construction numerous tests have been made of working parts and we have this basis for believing that the machine will function properly when completed. Our present estimate is that a properly trained technician, if he were allowed to put his entire time on this project, could finish it within two or three months, but it has (been) and will be necessary to do this work with small amounts of several individuals' time when they are not necessarily employed on those activities regarded as essential for the nation's welfare.[104]

Sympathetic to Atanasoff's plight, Poillon asked if additional money might help push the ABC along.[105] Atanasoff replied that the problem did not involve money, but rather:

> (The) necessity of using all possible technical help on an N.D.R.C. investigation which we are doing under the direction of Dr. Warren Weaver. Yesterday in the laboratory Dr. Weaver suggested that it might not be entirely right to defer the construction of our computing machine too much in favor of the other work, because the computing machine itself probably carries some implications in connection with the national defense.
>
> I judged from your letter that you would prefer that we push construction on this machine even if the costs are somewhat greater (then) under present circumstances. In view of this and Dr. Weaver's remarks, I shall attempt to advance the construction of the machine as rapidly as circumstances permit.[106]

Note that Weaver recognized potential for the ABC for defense, even if electronic digital computers had not yet become a priority. Soon after this, Berry found a permanent job on the West

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[102] Clifford Berry quoted in a transcript for "Iowa State Today," a radio news program hosted by Ione McNay, 1 May 1942, 4. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 5).

[103] J. V. Atanasoff, copy of letter to Howard A. Poillon, President, Research Corporation, 9 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

[104] John V. Atanasoff, copy of letter to the Research Corporation, 9 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

[105] Howard A. Poillon, letter to J. V. Atanasoff, 14 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

[106] John V. Atanasoff, copy of letter to Howard A. Poillon, President, Research Corporation, 24 April 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).

coast and prepared to leave ISC. He had been looking for a suitable position, hoping to avoid the draft while supporting a wife and helping his mother.[107] Atanasoff testified that for the few months before Berry acquired the job, the local draft board had put heavy pressure upon him, and as a consequence, Berry was not his normal self and got little accomplished.[108] Furthermore, the Navy was pressuring Atanasoff to help with its research.[109] He considered several possibilities, and in early June flew to San Diego to spend a week examining a Navy sound laboratory.[110] In California, he wrote to Legvold that he hoped Berry might complete the ABC in his absence.[111] Berry did not, and Atanasoff made the following request of Poillon at the end of the month:

> We are aggressively continuing the work on the computing machine. I am losing the services of Mr. Berry, who has been my assistant since the beginning of the project, but I now have another man, Harry Frissel, to work on this project. Besides, I have the part time services of an excellent mechanic and some other technical assistants.
>
> I wish you would consider the possibility of giving this project some defense status so we could claim deferment for Mr. Frissel and, perhaps, also for our mechanic. Do you think that such steps would be justified, and if so how should we go about it?[112]

It might seem odd that Atanasoff asked the Research Corporation about defense status, since it had no authority over such designations. However, as noted, Carroll Wilson was both an official within the Research Corporation and Bush's right-hand man at the OSRD. Even so, Bush had no special powers with the Selective Service and expended considerable energy attempting to get exemptions for scientists, not always successfully.[113] Still, Atanasoff thought that if the NDRC took the ABC under its wing, he might gain leverage. Poillon and Wilson batted the issue around, perplexed on why the ABC should not have a role in the national defense.[114] However, Poillon also warned Atanasoff that NDRC sponsorship did not guarantee deferments but might jeopardize his

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[107] Atanasoff, interview with Tropp, 7 June 1972, 194.
[108] *Honeywell*, "Transcript of Proceedings," 2,725-2,726.
[109] Atanasoff, interview with Kaplan, 10 August 1972, 56-57.
[110] Atanasoff, interview with Henry Halladay, et al., 23 July 1968, 44-45.
[111] John V. Atanasoff, letter to Sam Legvold, 10 June 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 11).
[112] John V. Atanasoff, copy of letter to Howard A. Poillon, President, Research Corporation, 29 June 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4).
[113] G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: The Free Press, 1997), 151-153 and 185-186.
[114] Carroll L. Wilson, Research Corporation, Boston, copy of letter to Howard Poillon, 6 July 1942; Carroll L. Wilson, Research Corporation, Boston, copy of memorandum to Howard Poillon, 14 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).

patent rights.[115] That probably helps explain why Atanasoff did not push harder for defense status for the ABC, and why he remained silent about it during the next crucial months.[116] Poillon had to conclude: "As I see it now, if he (Atanasoff) would have to shift a project (the ABC), which was of secondary importance to the war effort, over to N.D.R.C. to obtain exemption for his assistants, it would not be proper and investigations (on the ABC) could be better suspended until happier days."[117]

In setting the ABC aside, Poillon, Wilson, Weaver, Caldwell, Atanasoff, and probably, Bush were not being shortsighted but realistic and selfless. These people and others saw merit to electronic digital computers, and even had professional and economic interests in them, but now the nation had to put its resources where they could do the most good for the war, and such computers simply had not yet risen to the top of that list.[118] It was unfortunate that when calculating ballistics tables finally became a priority for the Army, Mauchly and Eckert were the ones available for the task, and they incorporated technologies in the ENIAC far behind those defined by Atanasoff, Berry, and others before the war. Electronic digital computers therefore got off on the wrong foot. Commercialization of the ABC could have been immediate, instead of the years it took because war and government intervened. As noted, low-cost, special-purpose or limitedly general-purpose computers for all manner of purposes could have been built based on the ABC without extensive development. Recall that the idea of general-purpose computing, but not the stored-program concept, was already well known and posed no particular conceptual problems. In going beyond the ABC, designing a sufficiently advanced memory posed the greatest challenge, just as with the NOL or IAS computers. However, in the case of ballistics equations specifically, there was nothing essential about doing the whole job numerically, and the ABC with the integrating attachment that Atanasoff envisioned could have been brought into operation quickly and handled the ballistics tables effectively and cheaply.

Another reason Atanasoff did not make greater effort to have the NDRC sponsor the ABC was due to his lose of Berry, who graduated in June 1941 in physics with a thesis entitled "Design of Electrical Data Recording and Reading Mechanism." The project pertained to recording and reading of binary numbers by the ABC. Berry began his thesis by noting: "In order to realize to the fullest

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[115] Howard A. Poillon, letter to John V. Atanasoff, 10 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 26, folder 4); Howard Poillon (attributed), copy of letter to (Carroll L.) Wilson, 9 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).
[116] Atanasoff, interview with Kaplan, 17 July 1972, 23.
[117] Howard Poillon (attributed), copy of letter to (Charles L.) Wilson, 17 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 7).
[118] For example, see Atanasoff, interview with Kaplan, 17 July 1972, 15.

extent the high-speed capabilities of the computing machine proper it is necessary to record and read numbers on cards at rates of the order of 60 holes per second." That ambitious goal beyond the capabilities of existing EAM equipment was selected to synchronize the operations of the read-write system with the rest of the ABC, and involved punching holes in paper cards using high-voltage arcs and reading back with lower-voltage arcs that could pass through the cards only at holes. Berry considered various circuits and selected two, one for punching and another for reading, promising economy and success. Always the consummate engineer, Berry designed circuits to operate under large tolerances.[119] He then began a Ph.D. degree in physics, also under Atanasoff, and continued to develop the circuits.

Berry, with Weiseman, finished the binary input and output devices but had trouble getting the system to function perfectly.[120] He and Atanasoff decided the problem might be solved with better paper, since one sample performed well. Unfortunately, they did not find a regular supply.[121]

Surprisingly, IBM had the same problem. Its recording equipment punched holes mechanically, but its readers detected the holes electrically using brushes. Contaminants caused false readings often enough that IBM established a laboratory to develop paper specifications and to analyze incoming stock, and gave justification to its demand that customers purchase cards exclusively from it.[122]

The binary recording and reading devices on the ABC operated at much higher voltages than the reading circuits on IBM equipment and, therefore, were far more sensitive to imperfections in the paper. Atanasoff and Berry had originally thought that IBM card stock might be satisfactory,[123] given IBM's exacting standards, but that failing and finding no other available paper suitable, Atanasoff thought he might take raw paper and finish (or size) it to his own specifications.[124] That plan had to be put aside because of the war.

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[119] Atanasoff, interview with Kaplan, 23 August 1972, 103-106; Clifford Edward Berry, "Design of Electrical Data Recording and Reading Mechanism," unpublished M.S. thesis, Iowa State College, Ames, Iowa, 1941, 3, 8, 11-23, and 30.

[120] Atanasoff, interview with Kaplan, 16 August 1972, 2-3.

[121] Atanasoff, interview with Tropp, 7 June 1972, 191-93; Atanasoff, interview with Kaplan, 23 August 1972, 48-49.

[122] Emerson W. Pugh, *Building IBM: Shaping an Industry and its Technology* (Cambridge, Massachusetts: MIT Press, 1995), 60.

[123] Berry, "Design of Electrical Data Recording and Reading Mechanism," 5.

[124] Atanasoff, interview with Kaplan, 10 August 1972, 25-27; John Vincent Atanasoff, New Market, Maryland, interview with B. Kaplan, 16 August 1972, 1-3; Atanasoff, interview with Kaplan, 23 August 1972, 48-49 and 103-105. Smithsonian.

Berry and Jean Reed married in a garden ceremony on the ISC campus on 30 May 1942. Atanasoff did not approve of the marriage. He believed their personalities too different, but wisely he said nothing.[125] One month later, Berry and his bride left for Pasadena, California, where he had a job with Consolidated Engineering Corporation (CEC), a firm founded by the son of Herbert Hoover. As one product, CEC produced mass spectrometers, instruments that sort molecules by mass and thereby analyze chemicals. The oil and gas industry in particular found mass spectrometers useful, but the process of analysis resulted in sets of linear algebraic equations. Thus, CEC had great interest in the ABC, but Berry could only disclose generalities without a patent application on file.[126] However, although assigned to mass spectrometers at CEC, Berry led a team that in 1945 produced a popular commercial analog computer, the Model 30-103 Electrical Computer, that could solve algebraic equation sets up to twelve unknowns.[127]

Incidentally, CEC changed its name to Consolidated Electrodynamics Corporation (still CEC) and moved into commercial electronic digital computers. In 1956, it sold its computer division, Electrodata, to Burroughs.[128] In 1986, Burroughs merged with Sperry Corporation (formerly Sperry Rand). Berry had little involvement in CEC's digital computers, but he became a recognized authority in mass spectrometers. At his death, he held thirty-three patents, with another eleven pending. Most dealt with mass spectrometry. He had also authored seventeen technical publications, most single author.

Berry leaving spelled the end of the ABC, because Atanasoff did not attend to it during his final two months at ISC.[129] Mather had left shortly before Berry to take a job at the NOL. Atanasoff hired Harry Frissel to replace them but provided him with minimal guidance. Atanasoff, remember, depended upon Berry for practical understanding of the ABC. Frissel, a graduate student in physics, had several weeks with Berry, and although he had no experience in electronics, believed he understood the ABC. He thought it complete and spent his time investigating paper for binary punch cards. He recalled Atanasoff being quite enthusiastic about the ABC, considering it "vital," but saw

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[125] Atanasoff, interview with Tropp, 7 June 1972, 188-189.

[126] Cliff (Berry), letter to J. V. Atanasoff, 26 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 24).

[127] Clifford E. Berry, et al, "Computer for Solving Linear Simultaneous Equations," *Journal of Applied Physics* 17, no. 4 (April 1946), 262-272.

[128] Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988), 67.

[129] Atanasoff, interview with Kaplan, 16 August 1972, 5-6.

little of him and made no progress as a result.[130] However, even if Frissel did not know, Atanasoff thought that the ABC contained a few minor wiring problems. Mid-summer, he wrote to Mather that the "maze of wiring still hides several 'bugs!'"[131] In August, Atanasoff wrote to another ex-student: "The computing machine is not finished, and I have been forced to the conclusion that I must abandon it for the duration. The difficulty is that I cannot keep men working on it under the present circumstances."[132]

Atanasoff worked hard his last summer in Ames to wrap up Project X. The OSRD wanted to extend the contract until 1 February 1943. However, Atanasoff decided that all related research worth doing could be completed by September 1. At end of July, he offered his services to the government however else it might need them.[133] A month later, he wrote to his parents: "It is commencing to seem likely that I will feel duty bound to take a position on the east coast for the duration of the war."[134] The NOL by then had taken a keen interest in Atanasoff. Although he had little knowledge of acoustics, his expertise in crystal physics and electronics made him invaluable for development of instrumentation for acoustic testing.[135] By September 2, the red tape had been mostly cleared, including taking leave of absence from ISC and arranging for Legvold to handle his classes, and the Navy told Atanasoff to report for duty in Washington, D.C., on September 14.[136]

Atanasoff went to the NOL because he felt it his patriotic duty. Still, he might have found another defense project at ISC. With the school already topsy-turvy due to the war, in January 1942 he took it upon himself to write to the NDRC, which preferred giving its lucrative contracts to the

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[130] Harry F. Frissel, Holland, Michigan, tape-recorded interview over telephone with Paul Mobley, 19 March 1998; A. L. Rosene, Field-Hamilton-Smith Paper Company, Omaha, Nebraska, copy of letter to Harry F. Frissel, 21 August 1942. Engineering Services Group, Ames Laboratory. See files of Gary A. Sleege.

[131] John V. Atanasoff, copy of letter to Bob (Mather), 3 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 13).

[132] John V. Atanasoff, copy of letter to George (Gross), 20 August 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 7, folder 13).

[133] Atanasoff also offered his services, and that of two of his students, to Harvard University on a NDRC project it had in acoustics. John V Atanasoff, copy of letter to Frederick V. Hunt, Harvard University, 29 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 12, folder 5); John V. Atanasoff, copy of letter to J. C. Morris, Director Office of Scientific Personnel, National Research Council, Washington, D.C., 28 July 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 9, folder 4).

[134] John V. Atanasoff (attributed), copy of letter to his parents, 24 August 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 7, folder 2).

[135] Atanasoff, interview with Kaplan, 23 August 1972, 92-95.

[136] J. V. Atanasoff, copy of letter to Jay W. Woodrow (on vacation in Colorado), Head of Physics Department, 2 September 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 11, folder 20).

same elite institutions represented by its officials, that ISC was being underutilized. ISC had three NDRC projects, his and two in chemistry, but he believed more ISC scientists should be involved.[137] The following month, the OSRD established the Ames Project at ISC to purify uranium for the atomic bomb, but presumably Atanasoff's letter had no impact on that decision.[138]

Of course, leaving Iowa gave Atanasoff the opportunity to become involved in the "big science" projects that the war established. It also increased his salary significantly. Finally, his marriage was in trouble and going to the NOL provided a way out.[139] To this point in his life, Atanasoff had put the preponderance of his formidable energies into his professional work; his family had never gotten more than an afterthought. For instance, Lura Atanasoff testified that her ex-husband had spent "every spare minute working on his computer," first "dreaming" about it, then building it: "Well, of course, that affects a family," she recalled.[140]

Leaving Ames did not solve his personal problems, and perhaps only aggravated them. He had always left most family matters to his wife, so that did not change, but now he was far away and unable to assist when needed. Sadly, his wife desperately needed his help. In November 1943, Gaskill wrote to him most urgently as follows:

> I am distressed by Mrs. Atanasoff's condition . . . (and) suggest that you return for a brief 'check up' on your family. Apparently Elsie's remarkable recovery which I reported to you verbally recently in Washington was premature and optimistic. She has recently been confined again to bed and I think Mrs. Atanasoff is very greatly in need of confidence and reassurance from you. She has undoubtedly gone through severe strain and has not wanted you to know.[141]

Elsie had severe asthma, a condition afflicting most of the family to a lesser extent. Some months later, and after weeks of frantic and lonely preparation, Lura Atanasoff loaded her children, and a kettle of boiled hypodermic needles needed to give Elsie her shots, into the family car and moved to Florida. Atanasoff thought Florida had a healthful climate, and he wanted his family where his relatives could help. However, Elsie spent much of her time there in a hospital, so Lura Atanasoff

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[137] John V. Atanasoff, copy of letter to Karl Compton, MIT, 15 January 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 7, folder 2).
[138] Carolyn Stilts Payne, "The Ames Project: Administering Classified Research as Part of the Manhattan Project at Iowa State College, 1942-1945," unpublished dissertation, Iowa State University, Ames, Iowa, 1992, 48 and 51.
[139] Gather, interview with Mobley, 1 July 1998.
[140] *Sperry Rand*, "Deposition of Lura Atanasoff," 6-7.
[141] Harold V. Gaskill, letter to J. V. Atanasoff, 18 November 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 5).

moved again, this time to Boulder, Colorado.[142] Atanasoff visited home perhaps six times during the war[143] but mostly worried helplessly.

Over a month before leaving Ames, Atanasoff sent Trexler, recently promoted to full partner, a package of information to be used in a patent application. It included a written description prepared mostly by Berry, associated drawings, and a list of claims that Atanasoff proposed. He kept the claims simple upon advice from the Patent Office.[144] The drawings were not finished, but Atanasoff wanted Trexler's criticisms first.[145]

Unfortunately, Trexler had started a large legal case that he could not relinquish. He proposed that someone else handle the application until he could be freed, but Atanasoff refused.[146] Trexler did not thus turn his attention to the ABC until November.[147] By then Atanasoff had been at the NOL for a couple of months. At first, Trexler thought the materials essentially complete,[148] but upon close study found references to drawings he did not have. Just before Christmas, he asked for an explanation.[149] Atanasoff responded in early January that the omissions were deliberate. He and Berry had decided that the drawings sent represented a "continuous and quite complete picture."[150] Trexler insisted on having the others, because they showed components that "are integral parts of the machine which must be disclosed."[151] Atanasoff did not agree, but asked Legvold at ISC to forward

[142] Gather, interview with Mobley, 1 July 1998; J. V. Atanasoff, copy of letter to H. V. Gaskill, 2 August 1945. ISU, Parks, "John Vincent Atanasoff Papers" (box 14, folder 5).
[143] Atanasoff, interview with Henry Halladay, et al., 23 July 1968, 20 and 22.
[144] Quincy C. Ayres, copy of letter to John V. Atanasoff, 16 October 1941. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[145] John V. Atanasoff, copy of letter to Richard Trexler, Cox, Moore, and Olson, 5 August 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[146] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to John V. Atanasoff, 21 August 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[147] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to John V. Atanasoff, 21 October 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[148] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to Wallace E. Barron, ISC, 21 October 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[149] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to John V. Atanasoff, 22 December 1942. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[150] John V. Atanasoff (attributed), copy of letter to Richard Trexler, Loftus, Moore, Olson & Trexler, 6 January 1942 (actually 1943). ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[151] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to John V. Atanasoff, 13 January 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).

the omitted drawings.[152] Legvold could not locate the drawings,[153] and in March, Atanasoff visited ISC. Atanasoff did not find the missing drawings either, but remained as enthusiastic as ever about the ABC. He therefore arranged for new ones to be made.[154] They were completed,[155] but then Trexler asked for revisions to the written description. Months went by with Trexler prodding Atanasoff to finish,[156] and then the records stop. The last correspondence until years later came in November 1943, when in a letter, Trexler warned Atanasoff not to delay in revising the description because of the "current activity in electronics and calculators."[157]

So why did the ABC not get patented? No one during litigation could explain, including Atanasoff, although he tended to blame ISC and Trexler.[158] Trexler stated during deposing that, "there was no definite reason why it (the application on the ABC) was not filed. It just was not filed. We just did not complete it."[159] In his defense, Trexler had suggested to Atanasoff at the beginning that he consider filing multiple applications instead of one that covered everything, and that might have made it easier to get at least part of the ABC patented.[160] At ISC, R. E. Buchanan faulted the war. "Had it not been for war interference," he averred, "I believe our Research Foundation would have played a large part in computer development."[161] Weight of evidence suggests that Buchanan had it most right. All agreed, however, that the ABC was an invention well worth patenting.

The world's first electronic digital computer got stripped and consigned to the junk pile, instead. Legvold eventually joined Atanasoff at the NOL. Moreover, he finished his Ph.D. degree

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[152] K. (Miss Kimmell of Trexler's Washington office), copy of letter to (Richard) Trexler, 25 January 1943. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 7).
[153] Sam (Legvold), letter to J. V. (Atanasoff), circa late January 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 11).
[154] Wallace E. Barron, Acting Secretary-Manager, copy of report to the Trustees of the ISC Research Foundation, 31 March 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).
[155] Sam (Legvold), copy of letter to J. V. (Atanasoff), 5 April 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 11).
[156] Richard Trexler (attributed), Loftus, Moore, Olson & Trexler, copy of letter to John V. Atanasoff, 29 June 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 4).
[157] Richard R. Trexler, Loftus, Moore, Olson & Trexler, letter to J. V. Atanasoff, 29 November 1943. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[158] Atanasoff, interview with Kaplan, 17 July 1972, 23-24; Atanasoff, interview with Kaplan, 16 August 1972, 21.
[159] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823-15,824, "Deposition of Richard R. Trexler," 19 June 1968, 9. ISU, Parks, "John Vincent Atanasoff Papers" (box 28, folder 6).
[160] Richard R. Trexler, Cox, Moore & Olson, letter to John V. Atanasoff, 19 December 1940, 1. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 22).
[161] Robert E. Buchanan, letter to Dan Griffen, ISU, 10 July 1963. ISU, Parks, "John Vincent Atanasoff Papers" (box 47, folder 3).

there under Atanasoff, since Atanasoff remained on the ISC faculty. Legvold graduated with a dissertation entitled "Naval Ordnance Laboratory Report #831."[162] ISC got one copy and locked it in a safe. Anyone who read it had to have proper security clearances. Legvold returned to ISC in 1946 and become a faculty member in physics. He asked Atanasoff, first in 1946 and again in 1947, if he could revitalize the ABC. He even found an interested graduate student.[163] Atanasoff, still at the NOL, approved.[164] However, Legvold got little accomplished before it was too late.

The ABC required rebuilding because graduate students had been robbing parts. Berry himself had a hand in that. In 1948, he finished a doctorate under Legvold with a dissertation entitled "Effects of Initial Energies on Mass Spectra." He conducted his research at CEC under physicist Harold Washburn but made it back to ISC intermittently. When there, students eagerly sought his help. For example, Harry Svec, ISU Distinguished Professor Emeritus of Chemistry, remembered Berry, with perhaps the glint of a tear in his eye, telling him what parts to take from the ABC to use in fabricating a mass spectrometer for his graduate research.[165]

Then, with available space in the Physics Building scarce, Gerald Fox, by now head of a growing physics department, told a student that if he cleaned the area where the ABC was stored, he could use it as a laboratory. Thus, without Atanasoff's permission, the ABC got stripped of its remaining usable parts and scrapped by Robert Stewart, who later worked with Atanasoff at the NOL and finally became chairman of the computer science department at ISC. Stewart had no idea what it was he junked, but recalled years later that he probably had to disassemble the ABC to allow its safe removal up rickety stairs and out the basement. Atanasoff felt certain that Fox ordered the ABC destroyed out of spite, but Stewart had no sense of that.[166]

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[162] "Minutes of the Meeting of the Graduate Committee," ISC, E. W. Lindstrom presiding, 10 January 1946. ISU, Parks, "Vice-President for Research Graduate College, Graduate Committee Files, 1913-61" (box 5).
[163] Sam Legvold, letters to J. V. Atanasoff, 1 July 1946 and 28 May 1947. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 11).
[164] *Honeywell*, "Transcript of Proceedings," 2,740-2,751.
[165] Svec became friends with Berry while work on the ABC was underway and observed its construction. He agreed with others that Atanasoff and Berry were both intense men who seemed to have contributed equally to the ABC. Coincidentally, both Berry and Svec had careers in mass spectrometry, Berry in industry and Svec at ISC. They kept in touch until Berry died. Harry J. Svec, tape-recorded interviews by telephone and in person with Paul Mobley, 12, 13, and 20 March 1998.
[166] Robert M. Stewart, Ames, Iowa, tape-recorded interview with Paul Mobley, 14 and 18 November 1997; John Vincent Atanasoff, Monrovia, Maryland, transcript of tape-recorded interview with William R. Turner, 27 October 1986, 30. ISU, Parks, "John Vincent Atanasoff Papers" (box 20, folder 3).

Atanasoff became Chief Scientist, Army Field Forces, in 1949. In 1951, he went back to the NOL as director of the Navy Fuze[167] Program. He left in 1952 to establish The Ordnance Engineering Corporation, which he and other shareholders sold to Aerojet-General Corporation in 1956. He stayed on as an executive until resigning in 1961. He voiced regret at having spent so much of his career in weapons research, but never lost interest in computers. Meeting with Sperry Rand in 1959, for example, he inquired if it might have need for a "machine in which the operating characteristics would be somewhere between a desk calculator and a punch card input electronic tabulator."[168] About this same time, he discussed with Berry his plans for a binary pneumatic digital computer.[169] He did nothing with these ideas, however.

Atanasoff and his wife divorced in June 1949. He married Alice Crosby two days later. Originally from Webster City, Iowa, Crosby went to Washington, D.C., during the war and learned drafting. The two met when she did work for him.[170] They made a good couple, helped, no doubt, by his mellowing slightly with time. Happily, time also brought him closer to his children. What is the purpose of life? Feeding babies, according to Atanasoff in his autumn years. Preoccupied during his children's childhoods, he found enjoyment in their children.

Ex-wives have a reputation for being bitter, but Lura Atanasoff spoke of her former husband with admiration. She testified that he was "really kind," "always doing good for people," and a man who always spoke the truth.[171] Similarly, Atanasoff was quite proud of his ex-wife. She proved as remarkable as he. The climate in Colorado agreed with Elsie, so Lura Atanasoff and her children settled permanently in Boulder. She taught Navajo children who had tuberculosis. As part of that experience, she developed her artistic talents and became a self-supported artist of some renown.[172]

Sadly for such a genuinely decent and creative person, Berry's story ended tragically. He had a solid marriage and two children, despite Atanasoff's misgivings. His life went downhill after an automobile wreck in 1957. Driving to work one morning, he got bumped from behind at an

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[167] Fuze was the Navy spelling for fuse.

[168] R. H. Sorensen, Assistant to the Vice President of Engineering, Remington Rand, Division of Sperry Rand, letter to John V. Atanasoff, 17 April 1959. ISU, Parks, "John Vincent Atanasoff Papers" (box 6, folder 6).

[169] Clifford E. Berry, letter to J. V. Atanasoff, 13 May 1959. ISU, Parks, "John Vincent Atanasoff Papers" (box 25, folder 23).

[170] Atanasoff, interview with Turner, 27 October 1986, 76-77.

[171] *Sperry Rand*, "Deposition of Lura Atanasoff," 16, 24, and 33; Philip Hart, as another, described Atanasoff as "warm and caring." Philip J. Hart, letter to Clark R. Mollenhoff, 17 September 1988. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 3, folder 30).

[172] Gather, interview with Mobley, 1 July 1998; Joanne Gather, Laguna Miguel, California, tape-recorded interview over telephone with Paul Mobley, 6 July 1998.

intersection. Berry exchanged information with the other driver, got back into his car, but then blacked out and hit a parked car himself. His physician suspected that antihistamines he took to counter an allergic reaction to a tetanus shot might have been a factor. In any case, Berry sustained brain and spinal damage that left him susceptible to convulsive seizures.[173] Moreover, although a star within CEC, he became unhappy after it was acquired by Bell & Howell Company. At some time in this, but probably as a result of the automobile wreck, he began drinking heavily. By 1963, he had shaken his alcohol problem, although he may have backslid. He took a job with Vacuum Electronics Corporation (VEECO) on Long Island, New York. Leaving his wife in California to wrap up matters there, Berry began his new job. He died in the hotel in which he lived on 30 October 1963. He had suffocated, a plastic bag tied with shoestrings over his head.[174] The death was ruled a suicide, but both Jean Berry and Atanasoff suspected murder. Atanasoff reached his conclusion after personally investigating several years later,[175] but whatever evidence he found was not enough to convince the police to reopen the case.[176]

The ABC was never forgotten completely. Both Atanasoff and Berry had discreet inquiries over the years, mostly from lawyers representing computer firms.[177] Atanasoff's meeting in 1959 with Sperry Rand was part of an investigation it conducted into the ABC, for example.[178] The representative for Sperry Rand noted that Atanasoff received him cordially but refused to allow a review of his records, and furthermore, for "personal and other reasons, Dr. Atanasoff seems anxious not to become embroiled in any legal entanglements on behalf of ourselves or others."[179]

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[173] Robert H. Pudenz, M.D., copy of letter to J. C. Conn, Driver Improvement Analyst, Department of Motor Vehicles, State of California, 13 May 1957; Robert H. Pudenz, M.D, copy of letter to Frank J. Weiss, 5 November 1957; G. Butler, Driver Improvement Analyst, Department of Motor Vehicles, State of California, copy of letter to Clifford Edward Berry, 29 May 1963; Jean Berry, letter to Clark R. Mollenhoff, 9 September 1986. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 7, envelopes postmarked 12 September 1986).

[174] Leon Schechterman, M.D., copy of autopsy of Clifford E. Berry, Suffolk County, New York, 30 October 1963. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 7, envelopes dated 12 September 1986).

[175] Jean Berry, letter to Clark R. Mollenhoff, 2 August 1988; John V. Atanasoff, copy of letter to (Chas. R.) Dillon, 15 February 1974. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 7, folder entitled "Jean Berry" and envelope from Clayton Morlan).

[176] For more on the death of Berry, see Mollenhoff, *Atanasoff*, 103-105 and 121-122.

[177] Atanasoff, "Advent of Electronic Digital Computing," 261.

[178] *Honeywell*, "Transcript of Proceedings," 2,305-2,308.

[179] R. H. Sorensen, memorandum entitled "Visit with Dr. J. Atanasoff," to C. A. Norton, T. C. Fry, F. J. McNamara, and H. Engstrom, 30 April 1959, quoted in *Honeywell*, "Transcript of Proceedings," 2,314-2,317.

The ABC finally became an issue with the awarding of a patent on the ENIAC in 1964. Eckert and Mauchly had by then sold much of their rights to it and other patents and applications to Remington Rand, which merged with Sperry Corporation in 1955 to become Sperry Rand Corporation. It assigned the ENIAC patent to Illinois Scientific Developments (ISD), a wholly owned subsidiary created for handling matters related to the patent.[180] Ensuing legal actions pitted Sperry Rand against other manufacturers of computers and associated equipment that desired to avoid paying the royalties demanded by Sperry Rand. Of note is a lawsuit filed in 1964 in which Sperry Rand sued the Control Data Corporation for infringing on the regenerative memory patent associated with the EDVAC. Tried briefly without resolution in 1972, *Sperry Rand v. Control Data Corp.* was finally settled outside of court for undisclosed terms in 1981.[181]

A second lawsuit involved the ENIAC patent and twenty-five other Sperry Rand patents and patent applications, including the regenerative memory patent. Most of these gave Eckert and Mauchly as the inventors or named Eckert alone.[182] The case began as two lawsuits filed the same day. On 26 May 1967, Sperry Rand sued Honeywell, Inc., in the U.S. District Court for the District of Columbia for infringing on the ENIAC patent. Honeywell had gotten into the computer business in 1955 in a joint venture with Raytheon. It soon bought out Raytheon's interests and made other acquisitions. By 1972, Honeywell had become a distant second to IBM in computer sales.[183]

A mere fifteen minutes earlier that same day, 26 May 1967, Honeywell had sued Sperry Rand in the U.S. District Court for Minnesota in Minneapolis. Honeywell initially charged Sperry Rand with violating the Sherman Act by enforcing a fraudulently procured patent. The suit at this point involved only the ENIAC patent. Honeywell sought damages and to have the ENIAC patent declared invalid and unenforceable. Honeywell later expanded its lawsuit to include other Sperry Rand patents and applications and a violation of the Clayton Act. They also added a charge under the Sherman Act dealing with an exclusive cross-licensing agreement that Sperry Rand entered into with IBM in 1956. Summarized briefly, in its legal actions Honeywell accused Sperry Rand of violating antitrust laws by

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[180] *Honeywell Inc. vs. Sperry Rand Corporation and Illinois Scientific Developments, Inc.*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, Earl R. Larson, "Findings of Fact, Conclusions of Law and Order for Judgment," 19 October 1973, sections 0.1.3 and 15.13.1. ISU, Parks, "Henry L. Hanson Papers" (box 5, folders 4-8).
[181] Atanasoff, "Advent of Electronic Digital Computing," 278. The patent involved in *Sperry Rand v. Control Data* was Patent No. 2,629,827. The legal case was often referred to as the regenerative memory case, or the Baltimore case, since it was assigned to the Federal District Court in Baltimore, Maryland.
[182] Burks and Burks, *The First Electronic Computer*, 196.
[183] Flamm, *Creating the Computer*, 113-116.

attempting to monopolize the computer industry, and with trying to charge royalties for patents that for a number of reasons were not valid or enforceable patents. The federal government consolidated all charges from the two lawsuits, and John Sirica, Chief Judge of the District of Columbia and later famous in Watergate hearings, assigned them to the U.S. District Court in Minneapolis as *Honeywell v. Sperry Rand and ISD.*

While preparing for trial, lawyers for Control Data and Honeywell came to realize that claims from the ENIAC, regenerative memory, and other Eckert-Mauchly patents derived in part from the ABC. A patent is awarded only for an original invention made by the claimant. Therefore, Control Data knew that if it could prove the connection between the work of Atanasoff and Berry and that of Eckert and Mauchly, it could invalidate the regenerative memory patent. Sperry Rand would then be forced to drop its suit and could not collect royalties. Thus, proving that connection became key to Control Data's defense strategy, although it did not make much in-court use of it because, as noted, the lawsuit eventually got settled outside of court.

For its part, Honeywell hoped to invalidate the ENIAC patent using the same plan of proving derivation from the ABC, among other unrelated strategies. Honeywell actually had easier way of invalidating the patent, although patents are generally assumed relatively secure from attack. Sperry Rand insisted that the ENIAC be recognized as the first automatic electronic digital computer, and that its patent be read so broadly as to cover almost all computers. To invalidate the ENIAC patent, then, Honeywell only had to demonstrate that the ABC was an automatic electronic digital computer that came before the ENIAC.[184] Honeywell did not need to prove the ENIAC derived from it. As the case turned out, Honeywell had it both ways by proving the ABC was the computer that came first and that the ENIAC depended upon it. Eckert, Mauchly, and Sperry Rand did not give in easily, however. Mauchly denied learning or using anything of importance from Atanasoff and Berry. He admitted telling Eckert about the ABC, but in his testimony Eckert agreed that the information had been of no value to them.[185] The evidence indicated the contrary, and for this reason and others,

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[184] The ENIAC patent is No. 3,120,606, "Electronic Numerical Integrator and Computer," filed 26 June 1947. On page 1, column 2, Eckert and Mauchly made the claim that the ENIAC "is the first general purpose automatic electronic digital computing machine known to us." If Sperry Rand had stood by this distinction of the ENIAC being general purpose, instead of insisting that it was the first electronic digital computer of any kind, its case might have done better in court.

[185] In testimony for *Honeywell v. Sperry Rand*, Mauchly said he had little memory of discussing the ABC with Eckert. In earlier deposition for *Sperry Rand v. Control Data*, however, he had said that he talked about it with a number of people at the University of Pennsylvania, including Eckert. *Honeywell*, "Transcript of Proceedings," 12,213-12,218 and 12,279-12,283; *Sperry Rand*, "Deposition of John W. Mauchly," 94.

Judge Larson declared the ENIAC patent invalid and unenforceable, as had been requested by Honeywell. He ruled the other Sperry Rand patents, including the regenerating memory patent, unenforceable but not invalid. Honeywell had not asked for a ruling on the validity of those patents.[186]

Honeywell v. Sperry Rand remains one of the longest and most complex federal trials in history. In 135 days of trial, lawyers from both sides introduced some 33,000 exhibits and heard depositions and testimony from 157 witnesses.[187] Honeywell won the lawsuit as a practical matter, although it did not win on all points or get damages it sought. Even before trial began, for example, Judge Larson disallowed Honeywell's charge under the Clayton Act. That charge dealt with the right of Remington Rand to buy the ENIAC patent. Then at close of trial, heard without a jury, Judge Larson ruled that Sperry Rand had not monopolized the industry, which concerned Honeywell's first charge under the Sherman Act. He did find that Sperry Rand had conspired with IBM to create a monopoly. This ruling dealt with Honeywell's expansion of their original charge under the Sherman Act. Moreover, Judge Larson believed Honeywell had suffered injury but awarded no damages because Honeywell had not acted with diligence.

Even without damages, the royalties Honeywell avoided paying by invalidating the ENIAC patent made the lawsuit worthwhile for it. Sperry Rand had demanded $250 million in royalties from Honeywell, although it eventually dropped the figure to about $20 million.[188] Moreover, Honeywell received some money because of the trial. Sperry Rand paid Honeywell not to appeal Judge Larson's decisions. The amount of money has not been disclosed, but Atanasoff understood it covered litigation costs for Honeywell. As badly as the trial went for Sperry Rand, it obviously believed the outcome could have been worse and did not appeal the rulings itself.

Atanasoff won little in the lawsuits other than the satisfaction of having the ABC legally recognized as the computer that came before the ENIAC, and therefore, for lack of evidence of an earlier one, as the first electronic digital computer. He received no financial gain from either trial other than consultant's fees. Early on, Atanasoff and Iowa State University (formerly ISC) sought to intervene in both lawsuits to have Atanasoff recognized as a joint inventor of the ENIAC and other

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[186] Henry Halladay, Dorsey, Marquart, Windhorst, West and Halladay, for *Honeywell*, "Plaintiff's Final Brief on the Merits," 30 September 1972, 481. ISU, Parks, "Clark R. Mollenhoff Papers, 1968-1990" (box 6).
[187] *Honeywell*, "Findings of Fact," sections 0.4 - 0.4.6.
[188] *Honeywell*, "Findings of Fact," sections 15.25, 15.25.12, 15.25.23.6, 15.28, 15.38, 15.39, 19.4, 19.5, 21.1-21.6, 24.1, and 26.1-26.1.4.

Eckert-Mauchly devices. If the interventions had been successful, patents involved could not have been declared invalid for reasons of derivation from him. If the patents had then withstood other legal attacks, Atanasoff and ISU could have made a lot of money. Atanasoff's name was not added to any of the patents, however. In the suit involving Honeywell, intervention was not timely. By the time Atanasoff and ISU agreed on terms of intervention, and after some legal maneuvering and a false start or two, Judge Larson ruled they were too late.[189] Litigation had progressed too far to be interrupted. The issue became moot when he declared the patents unenforceable or invalid for reasons other than derivation from Atanasoff. That is, it served no purpose to add an inventor's name to a patent already declared invalid or unenforceable. Likewise, once the regenerative memory patent was declared unenforceable in the Honeywell case, there was no reason to pursue intervention in the Control Data suit, which was settled later outside of court.

The computer industry as a whole came out the real winner in *Honeywell v. Sperry Rand.* Sperry Rand had been claiming nothing less than: "No data processing machine of any consequence . . . in the United States today is being made that does not make use of inventions covered by this (ENIAC) patent."[190] In other words, without considering its other patents, but based solely on the one for the ENIAC, Sperry Rand demanded the right to collect royalties for practically every computer made in the United States. They were asking major sums of money, too, as the experience of Honeywell attests. Had the patent been upheld, the computer industry might have been stifled for the seventeen-year life of the patent. Judge Larson's decisions therefore had momentous ramifications for the computer industry and the nation, but it got little news coverage. He released his decisions on 19 October 1973 in the midst of the turmoil surrounding the beginning of the end of the Nixon presidency. In particular, 20 October 1973 is the date of the infamous Saturday Night Massacre in which President Nixon had Watergate special prosecutor Archibald Cox fired, but not before Attorney General Elliot Richardson and Deputy Attorney General William Rickelshaus resigned rather than do the firing themselves. The resulting controversy pushed out other news.

Although the outcome of *Honeywell v. Sperry Rand* suggests that Mauchly stole ideas from Atanasoff and Berry for use in the ENIAC, that conclusion is unjustified based strictly on legally determined fact. Honeywell alleged that Eckert and Mauchly committed fraud by not crediting

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[189] Atanasoff, "Advent of Electronic Digital Computing," 273-274 and 278; For a summary of the details of the attempt by Atanasoff and ISU to intervene in the lawsuits, see Mary Greenwood, memorandum to Steve Knudsen, 28 November 1977, in ISU, Parks, "John Vincent Atanasoff Papers" (box 46, folder 5).

[190] The quotation is from *Honeywell*, "Findings of Fact," section 12.2.1.1.

Atanasoff's work, so Judge Larson considered the matter, but he did not find the two men guilty of fraud for that reason.[191] Nor did Judge Larson find fraud in ten other categories in which Honeywell charged fraud.[192] Fraud found in all cases would have been against the Patent Office, not against Honeywell or Atanasoff. The standard of evidence for a finding of fraud is high, however. As Judge Larson put it, a finding of fraud requires more than a preponderance of evidence; it requires "clear and convincing evidence."[193] Evidence presented by Honeywell fell short of that rightly rigorous standard, although Judge Larson gave the impression in a "Findings of Fact," in which he presented his verdict, that if evidence for a finding of fraud in several categories fell short, it fell short by not much.

Indeed, while not finding enough evidence of "willful and intentional" fraud to warrant invalidating the patent on that basis, Judge Larson found enough "inequitable conduct" to declare the patent unenforceable.[194] His citations of "various derelictions of Eckert and Mauchly and their counsel" in pursuit of the ENIAC and other patents do cast them in suspicious light. Evidence suggested that they had suppressed information, withheld documents, and made misleading statements, among other reprehensible behaviors. Even so, in each case Judge Larson added that extenuating circumstances might absolve Eckert and Mauchly of some guilt.[195]

As one example, Judge Larson considered the issue of "delay before the Patent Office" as an area of potential fraud related to the ENIAC patent. Approval of the patent application took almost seventeen years, and much of that extraordinary approval time resulted from interferences that Eckert and Mauchly with Remington Rand or Sperry Rand instigated. From 1951 through 1957, for example, after the ENIAC patent application had been filed, they "copied" 152 claims from other patents and then initiated interferences while the claims were sorted out. The Patent Office ruled against them on 147 of those claims, and Judge Larson believed many had been "unwarranted." The interferences served not to gain credit for other inventions, or to protect the ENIAC, but to take up

[191] The legal actions rarely cited Berry, because Honeywell decided it better served its purposes to focus on Atanasoff.
[192] Judge Larson took all the complaints from Sperry Rand and Honeywell and parsed them into the decision categories that made up the sections in his "Findings of Fact." The first eleven sections deal with specific categories of complaints by Honeywell in which it asked for rulings invalidating the ENIAC patent. He then added a twelfth section, dealing generally with validity, and a thirteenth for fraud. These latter two sections, like the previous eleven sections, concern only the ENIAC patent. The "Findings of Fact" then addressed the other issues in additional sections.
[193] *Honeywell*, "Findings of Fact," section 13.1.
[194] *Honeywell*, "Findings of Fact," sections 12.3.3-12.3.3.20.
[195] *Honeywell*, "Findings of Fact," sections 13.12, 13.12.1, 13.12.17, 13.34, 13.36.1, and 13.37.7, as examples.

time. The longer it took to grant the ENIAC patent, the longer its effective life and greater its value. The interferences also gave Sperry Rand leverage in royalty agreements. Judge Larson believed that Eckert, Mauchly, and Sperry Rand had crossed ethical lines, although he also understood that a new technology like the computer might foster interferences while details got resolved. In the end he found delay, but not "intentional delay," and it was only "with reluctance" that he did not invalidate the ENIAC patent on that basis. Once again he ruled it unenforceable.[196]

As another example of misconduct, Eckert, Mauchly, and Sperry Rand modified the ENIAC patent application after its initial submittal to keep it current. In particular, they originally included a definition of "pulse," a word that gets at the essence of a digital computer, but that they had defined by its duration, or width, consistent with the ENIAC. By the 1960's, that definition had become inadequate to describe the narrower pulse widths of newer computers, so they modified the definition to cover all digital computers. Judge Larson ruled that they had thus "improperly broadened" the application and invalidated nine claims in which the word pulse or related words appeared.[197]

If not quite sufficient for a finding of fraud, ample evidence existed for Judge Larson to declare the entire ENIAC patent invalid and unenforceable in four separate categories of complaints. That is, of eleven categories of complaints filed by Honeywell specifically pertaining to the ENIAC patent, and in which it sought to rule the patent invalid for reasons of fraud, Judge Larson found blatant fraud in none. In four categories he nonetheless found justification to render the patent both invalid and unenforceable. These four are in addition to the two categories noted above, "delay" and "fraud," in which the patent was declared simply unenforceable. Furthermore, for various reasons he invalidated nineteen of 148 specific claims made in the ENIAC patent. It should be noted that Judge Larson did not examine all 148 claims in the patent, one by one, for validity. Rather, he considered a few claims as representative. Thus, that Judge Larson found nine claims had been improperly broadened means that nine claims had been improperly broadened out of seventeen claims he happened to consider. He did not examine the other 131 claims. It must also be noted that the seventeen representative claims were not chosen randomly, nor did Honeywell select them; rather, ISD picked them as evidence for its charge of patent infringement against Honeywell. It is therefore safe to assume that Sperry Rand used those claims because it believed they best represented its case

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[196] Judge Larson defined interferences as "proceedings in the Patent Office to determine who, between two or more parties, is entitled to priority of invention." *Honeywell*, "Findings of Fact," section 11.51; also sections 11.5, 11.5.5, 11.5.6, 11.14-11.14.5, and 12.3.2.
[197] *Honeywell*, "Findings of Fact," sections 10.1.6-10.1.7.

against Honeywell. In addition, Judge Larson invalidated three claims for "derivation from Atanasoff." These three include one on the ISD list.[198]

Concerning the patent as a whole, the four categories in which Judge Larson declared it invalid and unenforceable were "public use," "on sale," "publication," and of course, "derivation from Atanasoff." The first three deal with much the same thing: public disclosure. By law, once an invention has seen public use, been made available for sale, or had material of a substantial nature published on it, there is a one-year limit for submission of the patent application. The purpose is to ensure the public gets the benefit of inventions quickly. The application for the ENIAC was submitted on 26 June 1947, so the so-called critical, or one-year-prior, date was 26 June 1946.[199] Any disclosures before that date could have constituted grounds for invalidating the patent. Judge Larson determined that the ENIAC patent application had failed to meet the test of that critical date in the three public disclosure areas, and therefore, he ruled the patent invalid and unenforceable in each.

First public use of the ENIAC began late in 1945 for calculations on the feasibility of the "Super."[200] After its public unveiling in February 1946, the ENIAIC did other tasks of a public use nature before the critical date.[201] In addition to finding the patent as a whole invalid for reason of public use, Judge Larson invalidated all seventeen of the representative claims for the same reason.[202]

As for its sale, Judge Larson noted that the ENIAC had been built under contract to the Army, which took delivery on 31 December 1945.[203] That constituted sale of the ENIAC and made it necessary to invalidate the patent.[204] Judge Larson also found that *First Draft of a Report on the*

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[198] *Honeywell*, "Findings of Fact," sections 3.1.3 and 12.2.7.1 - 12.2.7.6. Specifically, Judge Larson invalidated all seventeen claims on the list submitted by ISD because of public use. These claims were 8, 9, 36, 52, 55, 56, 57, 65, 69, 75, 78, 83, 86, 88, 109, 122, and 142. He invalidated nine claims because they had been improperly broadened. These claims were 8, 9, 52, 65, 83, 86, 88, 109, and 122. Ten claims were invalidated because of their association with "The First Draft Report on the EDVAC." These claims were 8, 9, 52, 55, 56, 57, 65, 69, 75, and 78. Three claims, 83, 86, and 88, were invalidated because of the prior work of Byron Phelps, an engineer for IBM. Phelps had developed a multiplier similar to the one used in the ENIAC, both of which were based on the IBM 601 multiplier. In addition, Judge Larson found that claims 88, 89, and 90 were invalid because of the prior work of Atanasoff. How Judge Larson came to consider these three claims for derivation from Atanasoff is not clear. Arthur Burks said Honeywell submitted them for consideration (*The First Electronic Computer*, 242), but its summarization included only claim 89. *Honeywell*, "Plaintiff's Final Brief on the Merits," 84.

[199] *Honeywell*, "Findings of Fact," section 1.1.1.11.

[200] *Honeywell*, "Findings of Fact," section 1.1.4.

[201] *Honeywell*, "Findings of Fact," section 1.1.3.

[202] *Honeywell*, "Findings of Fact," section 12.2.7.1.

[203] *Honeywell*, "Findings of Fact," sections 2.1.3.10 and 2.1.5.5.

[204] Official acceptance by the Army did not occur until 30 June 1946. Goldstine, *The Computer from Pascal to von Neumann*, 234.

EDVAC, distributed in June 1945, violated the restriction against publication. Since von Neumann used the report to discuss the possibilities of computer design generally, he necessarily disclosed claims from the ENIAC patent. Judge Larson found ten of the seventeen representative claims invalid because of publication,[205] in addition to finding the entire patent invalid for the same reason.

Finally, Judge Larson invalidated the ENIAC patent and ruled it unenforceable because he determined that the ABC had been an automatic electronic digital computer that came before the ENIAC. Furthermore, he found that the ENIAC derived from the earlier computer. Derivation from the ABC was general, over the entire ENIAC patent, and by specific claims.

Both Mauchly and Atanasoff gave extensive testimony on the issue of derivation in pretrial depositions and in court. At the conclusion of the trial, Judge Larson said that he, "heard the testimony at trial of both Atanasoff and Mauchly, and finds the testimony of Atanasoff with respect to the knowledge and information derived by Mauchly to be credible."[206] Atanasoff was a man of integrity, and there is no record of him ever behaving otherwise. On the other hand, Judge Larson pointedly said nothing about the testimony of Mauchly, strongly implying that he believed it to have been less than credible. Indeed, Mauchly had dissembled, obscured, and evaded throughout.

In fairness, some of the difference in credibility in testimony may have been due to litigation tactics. Lawyers for Honeywell coached Atanasoff to remember details. Attorneys representing Mauchly apparently preferred that he did not. Furthermore, testifying became an ordeal for both men. Atanasoff suffered excruciating back pain[207] and Mauchly from poor health.[208] Regardless, the facts were undeniable, and Judge Larson found substantial connection between the ABC and ENIAC, noting that the, "work of Atanasoff was current and was of great importance to M" (Mauchly).[209]

Judge Larson carefully avoided saying Mauchly knowingly used ideas from the ABC in the ENIAC. On the other hand, had he considered derivation of the EDVAC, he might have found it difficult to avoid a verdict of fraud, much closer was it to the ABC. As it were, scrupulously fair and dealing only with issues specifically on the table, Judge Larson gave Mauchly the benefit of the doubt and declared, he "may in good faith have believed that the monstrous machine (the ENIAC) he helped to create had no relationship to the ABC."[210] This pronouncement may seem at odds with other of his

[205] *Honeywell*, "Findings of Fact," sections 12.2.7.6.
[206] *Honeywell*, "Findings of Fact," sections 3.1, 3.1.19, and 12.2.7.3.
[207] Atanasoff, "Advent of Electronic Digital Computing," 266-267 and 271.
[208] McCartney, *ENIAC*, 187.
[209] *Honeywell*, "Findings of Fact," section 13.19.
[210] *Honeywell*, "Findings of Fact," section 13.25.

statements, but it was not. Given wartime conditions, Mauchly and Eckert had access to almost any technology they might find useful, most in industry. Indeed, they began the ENIAC on the assumption that they need not develop any major circuits.[211] They borrowed ideas promiscuously and in most cases legitimately.

The ENIAC on that basis became a marvel of Rube Goldberg engineering. It consisted of thirty major electromechanical and electronic components initially developed mostly elsewhere and cobbled together. As an outfall, the various pieces of the ENIAC operated on some seventy-eight different voltages.[212] As examples of the motley genesis of the ENIAC, its multiplier was its most complex component. The ENIAC engineers based it on the IBM 601 cross-footing multiplier, the most powerful commercially available calculator. However, they improved it for the ENIAC by incorporating resister-matrix circuits independently invented by Perry Crawford, of MIT, and Jan Rajchman, of RCA. Resister-matrix circuits also formed the basis for the three function tables. Twenty accumulators of ten counters each formed the heart of the ENIAC, and the counters came from a design by Igor Grosdoff, of RCA, and modified by Eckert. Before selecting the RCA counter, several other electronic circuits had been considered, including one from NCR that could count at 100,000 cycles per second.[213] The ENIAC also incorporated a buffer storage made from relays and designed by Samuel B. Williams of the BTL,[214] and a card reader and cardpunch specially developed by IBM.[215] The Army gave IBM and the BTL specifications for the equipment without disclosing anything else.[216]

In short, the ENIAC had many parents, unlike the ABC, built from the ground up as one compact, integral, and original machine. Atanasoff and Berry even invented input and output units, although they did not work perfectly. The ENIAC crew did not attempt such difficult-to-build

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[211] Moore School of Engineering, "ENIAC (Electronic Numerical Integrator and Computer), Volume I, A Report Covering Work until December 31, 1943," 1-2. University of Pennsylvania.
[212] Arthur W. Burks and Alice R. Burks, "The ENIAC: First General-Purpose Electronic Computer," *Annals of the History of Computing* 3, no. 4 (October 1981), 337 and 355.
[213] Burks and Burks, "The ENIAC," 350, 351, and 362-369; "Report for Project PX: The NCR Thyratron Counter," circa September 1943. University of Pennsylvania.
[214] *Honeywell*, "Findings of Fact," section 4.2.7.
[215] Moore School of Engineering, "ENIAC Progress Report Covering Work from Jan. 1 to June 30, 1944," 1-5. University of Pennsylvania.
[216] Charles J. Bashe, et al., *IBM's Early Computers* (Cambridge, Massachusetts: MIT Press, 1986), 27; Goldstine, *The Computer from Pascal to von Neumann*, 164-165; John W. Mauchly, "The ENIAC," in *A History of Computing in the Twentieth Century: A Collection of Papers*, ed. N. Metropolis, J. Howlet, and Gian-Carlo Rota (New York: Academic Press, 1980), 548.

devices despite huge resources and despite a critical need for faster input and output.[217] Industry contributed to the ABC, but the ENIAC was unthinkable without its unstinting support.

Mauchly could have chosen any number of architectures in which to incorporate the sundry components, but rather than the ABC or IAS computer, he chose one like a differential analyzer. Analyzers at the University of Pennsylvania and Army labored full time at ballistics calculations during the war but fell further and further behind. The Army requested human computers be placed into service at the University of Pennsylvania, and when they proved insufficient, it funded the ENIAC. Since the Army had an established relationship with the University of Pennsylvania in ballistics, the school had an advantage in contractor selection.[218] Mauchly happened to be in the right place at the right time and, greater luck for him, with more knowledgeable authorities committed to higher priority projects. Fascinated by the differential analyzer, he took its distributed, or parallel, architecture for the ENIAC.

The ENIAC therefore inherited characteristics from a differential analyzer, despite the ENIAC being digital and analyzer analog. For example, just as the solution of an integral equation was distributed over parts of a differential analyzer for the coordinated and simultaneous execution of all terms, so too, the ENIAC could calculate with multiple numbers at the same time. Despite its highly parallel design, however, solutions on the ENIAC evolved sequentially, not simultaneously. It solved equations step by step, and at each step as dictated by programming, drew from components needed for that calculation.[219]

Mauchly thought the architecture of the differential analyzer the obvious model for the ENIAC.[220] After all, the ENIAC had to solve ordinary differential equations, because ballistics equations take that form, and that was also the purpose of a differential analyzer. Moreover, a differential analyzer was adaptable, and the ENIAC also needed flexibility, because no one knew what numerical algorithm might work best. As noted, computerized numerical methods did not become well defined until later. The Army could not simply automate what human ballistics computers had been doing, because the ENIAC could not handle an algorithm even that rudimentary.

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[217] Goldstine, *The Computer from Pascal to von Neumann*, 164.
[218] Nancy Stern, *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Bedford, Massachusetts: Digital Press, 1981), 10.
[219] Arthur W. Burks, "From ENIAC to the Stored-Program Computer: Two Revolutions in Computers," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 322-327.
[220] Moore School of Engineering, "ENIAC . . . A Report Covering Work until December 31, 1943," I(1)-I(3).

Designing adaptability into the ENIAC gave it capabilities to solve ballistics equations and print results into tables, and also allowed it to attack other types of equations.

A differential analyzer and a digital computer solved problems fundamentally different, however. By choosing the architecture he did, Mauchly made problem solutions more difficult than necessary. Like a differential analyzer, the ENIAC became a huge, complicated machine. If both could perform multiple tasks, the ENIAC more than the differential analyzer, neither could be conveniently reprogrammed. Preparing a differential analyzer to solve a new equation could take several days and involved taking the machine apart and bolting it back together in rearranged form. Likewise, the ENIAC could take a couple of days to program and involved reconnecting its numerous jumper cables and painstakingly resetting its switches. This meant the ENIAC, like a differential analyzer, was most useful when performing many calculations using the same equations.[221]

Performing many calculations with the same equations but slightly different variables met the Army's needs. It funded the ENIAC because it wanted ballistics calculations done faster. The University of Pennsylvania promised that could be accomplished with digital and vacuum tube technologies. Mauchly knew this was feasible because of the ABC. Even so, he did not choose the ABC as the model of how the ENIAC would compute. Rather, like his choice of architecture, he looked to familiar technology. He selected in this case the common mechanical calculators, with which he had experience. Hardly an original thinker, Mauchly conceived of the ENIAC as "exactly analogous to the ordinary mechanical computing machine."[222] Like the old machines, the ENIAC used decimal numbers, and its basic computational elements were accumulators, which combined arithmetic and memory functions. As an outfall, modeling the ENIAC counters on mechanical calculators meant that they too could compute with all digits simultaneously.

Thus, the essence of the ENIAC was that Mauchly replaced the integrators of the differential analyzer with electronic digital counters modeled on mechanical calculators.[223] Eckert and Mauchly added function tables, multiplier, and other components, following closely on Travis. Finally, they including manual programming apparatus derived from the plugboards of EAM equipment by

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[221] Burks, "The ENIAC," 340 and 344. See also Burks, *The First Electronic Computer*, 111.
[222] John W. Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," in *The Origins of Digital Computers: Selected Papers*, ed. Brian Randell. 3rd ed. (New York: Springer-Verlag, 1982), 356.
[223] Mauchly's decision to model the ENIAC on the differential analyzer and the mechanical calculator explains its highly parallel architecture. A differential analyzer performed multiple computations simultaneously, while the mechanical calculators typically computed with all digits in numbers at the same time. Mauchly selectively combined the features of the two machines to obtain in the ENIAC the most highly parallel computer possible. See Burks, *The First Electronic Computer*, 19.

IBM.[224] What might be loosely termed the ENIAC's software involved physically making wiring connections to get the computer to step through an algorithm for an approximate numerical solution to a differential equation or other mathematical problem. Mauchly noted that the ENIAC must have appeared nothing more than "a giant plugboard."[225] Described by major technologies from which it derived, an explanation of the ENIAC to the Army read as follows:

> (The ENIAC) should operate in steps rather than on the continuous variable principle of the differential analyzer. Such step operations requires the utilization of numerical calculating procedures, and in order to make such numerical calculating methods practical it is necessary to have a device which will operate at speeds far exceeding those of the usual mechanical computing machines.[226]

Publicity on the ENIAC always emphasized its speed. The following excerpt from an article by Arthur Burks was typical: "A skilled (human) computer with a desk machine can compute a 60-second trajectory in about twenty hours; a differential analyzer can produce the same results in about fifteen minutes; the ENIAC can do it in thirty seconds, that is, it can compute the trajectory of a shell faster than the shell itself flies!"[227] However, the only meaningful measurement is completed ballistics tables, and there the ENIAC lost much of its supposed advantage. From start to finish, the ENIAC actually could produce ballistics tables about eight times faster than a differential analyzer but cost thirty times as much.[228]

An Army review committee recommended that the officer who authorized the ENIAC be reprimanded for spending so much on something that did not contribute to the fight.[229] Nothing came of that, however, perhaps because the Army wanted to avoid adverse publicity. Instead of taking its lumps, the Army turned its sponsorship of the behemoth into a propaganda coup.

Although the ENIAC remained in service until October 1955, for most of that time it was a much different computer than the one that Eckert and Mauchly built. A 1948 modification, for example, gave it a serial architecture and capabilities to store a program internally. In 1953, it acquired an iron core memory.[230]

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[224] Burks, "From ENIAC to the Stored-Program Computer," 327.
[225] Mauchly, "The ENIAC," 547.
[226] Moore School of Engineering, "ENIAC . . . A Report Covering Work until December 31, 1943," I(3).
[227] Arthur W. Burks, "Electronic Computing Circuits of the ENIAC," *Proceedings of the I.R.E.* 35, no. 8 (August 1947), 756.
[228] The Differential Analyzer of Vannevar Bush cost $25,000. Zachary, *Endless Frontier*, 49; Burks and Burks, "The ENIAC," 372.
[229] Brainerd, "Genesis of the ENIAC," 488.
[230] Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 299.

Perhaps it was no wonder that Judge Larson questioned whether Eckert and Mauchly intended to deceive by use of technology from the ABC. By all appearances the ENIAC could not have been more different. Moreover, concepts used in the ENIAC came from a variety of sources under pressing circumstances, so he thought it might have been unreasonable to expect Eckert and Mauchly to have kept careful accounting.[231]

Furthermore, while evidence indicated that Mauchly had been impressed with the ABC, other evidence suggested that he had not intended to copy from it, at least for the ENIAC. Judge Larson cited a summary that Mauchly wrote in 1944 in which he made note of the ABC's motor-driven timing and rotating components. Mauchly went on to say that it, "was not by any means what I had in mind." The implication is that he had wanted a computer more electronic, and faster, than the ABC and rejected it as a model.[232]

In historical context, however, that summary looks questionable. Recall that after seeing the ABC, Mauchly asked to duplicate it. Then after the ENIAC proved a disappointment, Eckert proposed a motor-driven computer that sounded much like the ABC except with magnetic storage, which of course, Atanasoff had also proposed. Obviously, Eckert and Mauchly thought the motor-driven ABC had something going for it. Thus, in his summary, Mauchly may simply have been covering his and Eckert's tracks, since at the time, he and Eckert had decided to commercialize computing technology. Indeed, Mauchly wrote the summary just after visiting Atanasoff, which occurred the same day he and Eckert consulted with a patent attorney. In deposing, Mauchly recounted his surprise that Atanasoff that day showed little interest in computers and hinted that he was therefore justified in patenting features attributable to the ABC.[233]

As another note, Mauchly invited Atanasoff to the unveiling of the ENIAC, which does not sound like a man with something to hide. Of course, Mauchly was quite safe: no one could discern the connections with the ABC without careful study far beyond that obtainable from a casual viewing. Atanasoff did see the ENIAC, although it is not clear when, but received only superficial explanation. Furthermore, Mauchly always refused to discuss the ENIAC with Atanasoff, citing national security.

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[231] *Honeywell*, "Findings of Fact," section 13.23.

[232] John W. Mauchly, memorandum entitled "Situation as of September 10, 1944," quoted in *Honeywell*, "Transcript of Proceedings," 11,914-11,922; *Honeywell*, "Findings of Fact," sections 13.25-13.25.1.

[233] *Honeywell*, "Transcript of Proceedings," 12,281-12,282; *Sperry Rand*, "Deposition of John W. Mauchly," 190 and 198; *Honeywell*, "Findings of Fact," section 13.20.2.

Finally, Judge Larson pointed out that Atanasoff waited until the 1960s to present his case. If fraud had occurred, he should have spoken sooner.[234] In defense of Atanasoff, he entered litigation only after his professional life had wound down and at the behest of others, and it was through related discovery that he recognized that the ABC had been fundamental. Until then, with no obvious similarities between the two machines, he had not assumed there were important connections, although he had been given hints over the years.[235]

Instead of speaking of fraud based on derivation from Atanasoff and Berry, one might ask: Given that the ENIAC was modeled on a differential analyzer and mechanical calculator, and that the ABC and ENIAC were otherwise so different, how can any ideas in the ENIAC be said to have come from the ABC? Part of the answer is that Eckert and Mauchly wrote the ENIAC patent so broadly that it coincided in general terms with all electronic digital computers, including the ABC and true computers, with which the ENIAC also shared few characteristics.

Beyond that, it was difficult to make definitive comparisons between the details of the ABC and ENIAC. Both were complex machines. For the ENIAC, the patent contained enormous but often-vague information in its 91 drawings, 104 pages of specifications, plus 148 claims. For the ABC, while simpler than the ENIAC, there was little extant evidence to consider. What was known came mostly from the funding manuscript that Atanasoff wrote, from a description Berry prepared for a patent application, and from his thesis. Thus, there was too general information in the one case and too little in the other to easily determine how much of the ENIAC derived from the ABC.

Judge Larson selected three claims as having been derived from the ABC, but he could only say that those claims were representative. He made no attempt to consider all claims. Nor did Honeywell try to determine the extent of the derivation of the ENIAC from the ABC. Its litigation strategy avoided wrangling over individual claims.[236] Atanasoff himself could not say how much

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[234] Atanasoff did not attend the unveiling ceremony of the ENIAC but saw it later in association with the NOL computer project. *Honeywell*, "Transcript of Proceedings," 2,230; 2,234-2,240; 2,791; 2,799; 2,810-2,812; 2,822-2,824; and 2,828-2,829; *Honeywell*, "Findings of Fact," sections 13.20 and 13.25.2; Atanasoff, "Advent of Electronic Digital Computing," 256.

[235] Atanasoff, interview with Kaplan, 17 July 1972, 33-34; John V. Atanasoff, transcript of interview with Henry Halladay, et al., Dorsey, Marquart, Windhorst, West and Halladay, 24 July 1968, 9. ISU, Parks, "John Vincent Atanasoff Papers" (box 33, folder 1).

[236] *Honeywell*, "Plaintiff's Final Brief on the Merits," 48-49. ISD originally accused Honeywell of infringing upon claims 8, 69, 88, 89, and 147 of the ENIAC patent. See, Bruce E. Bremberg, President, ISD, letter to Henry L. Hanson, Corporate Patent Counsel, Honeywell, March 4, 1965. Honeywell considered those claims and found that, in its opinion, all five derived from Atanasoff. It did not bother investigating other claims in detail but nonetheless concluded that, "it is clear that the

came from the ABC. He instead focused on one claim, claim 100, as a flagrant example of technology used in both computers, but that was unlikely to have made its way into the ENIAC by coincidental discovery. Claim 100 was not considered in *Honeywell v. Sperry Rand*, however, so Judge Larson did not rule on it. The subject dealt with a special type of division called non-restoring division that Atanasoff invented, although he did not call it by that name. Atanasoff's funding manuscript covered the division, and adding insult to injury, he remembered explaining it to Mauchly during his visit in 1941 to Ames.[237]

Fortunately, Burks examined derivation from the ABC, and he was singularly qualified for the task. Although Eckert and Mauchly claimed to be its sole inventors, the ENIAC, like the EDVAC, involved the efforts of many people. Burks was one principal designer; Kite Sharpless and John Davis were others. The team included at least fourteen engineers and mathematicians besides Eckert and Mauchly, and not including Brainerd, who supervised.[238] Naturally there were hard feelings when Eckert and Mauchly designated themselves the inventors and got the University of Pennsylvania and the Army to support them as such.

Eckert did ask the other ENIAC designers of any claims they might have. At least Sharpless and Robert Shaw replied that they should be listed as co-inventors. Eckert had not been authorized to make the inquiry, however, and Brainerd reprimanded him. It may be that the others made no reply because Eckert had not acted in an official capacity.[239] If so, they made a mistake because they got no other opportunity to state their claims. Eckert and Mauchly thereafter ignored claims by others and demanded to be allowed to file for the patent as sole inventors and assignees. The University of Pennsylvania finally agreed to the former but not the latter. Eckert and Mauchly responded by threatening to quit work on the ENIAC if not given commercial rights, and never mind the war. Faced with not being able to fulfill its contractual obligations, the University relented. When Army

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work done by Atanasoff and Berry fully anticipates a significant number of the broader claims in the ENIAC patent." C. G. Call, memorandum to D. D. Allegretti, both of Bair, Freeman and Molinare, circa August 1967. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 11, and box 1, folder 13).

237 Atanasoff, "Advent of Electronic Digital Computing," 277; *Honeywell*, "Transcript of Proceedings," 2,164-2,165.

238 Goldstine, *The Computer from Pascal to von Neumann*, 155.

239 In reply to Eckert's inquiry about claims he might have, Arthur Burks stated that he had none. Later he decided that he should have been listed as co-inventor of a number of ENIAC components, explaining that he had originally misunderstood what it meant to be an inventor. "Affidavit of Arthur W. Burks" in "Documents Submitted by S. C. Yuter, J.S.D., Attorney for Professor Arthur W. Burks" to *Honeywell Inc. vs. Sperry Rand Corporation and Illinois Scientific Developments, Inc.*, United States District Court, District of Minnesota, Fourth Division, Civil Action File No. 4-67 Civil 138, 4 and 17-22. ISU, Parks, "John Vincent Atanasoff Papers" (box 42, folder 1).

attorneys then asked Eckert and Mauchly of any co-inventor claims by others, they said that there were none. The attorneys took the two men at their word. The other designers were not told of the agreement Eckert and Mauchly made with the Army.[240]

The Army for its part wanted a patent application filed quickly. It, like the federal government generally, maintained a "shop right" policy. It typically paid for employees' inventions, including patenting costs, in return for the right to use the inventions free of royalties.[241] The same held true for the NDRC, incidentally. Most patents resulting from NDRC contracts, paid for by taxpayers, went to the contractors.[242] In this case, the Army worried that Samuel Williams might file on a computer he was designing for the BTL before an application could be submitted on the ENIAC, and it might therefore lose free rights to technology inherent to both. Thus, when Eckert and Mauchly came out the winners in their haggling with the University of Pennsylvania, the Army asked few questions but quickly negotiated a deal giving it the same royalty-free use that had been part of the original agreement with the school.[243]

Contributing to the sense of injustice and a source of tension during the project was that Mauchly made little discernible ongoing contribution. He was not even an official member of the team; Brainerd designated him a consultant instead. As such, he spent much of his time writing progress reports, a task he did poorly. He performed better helping to integrate old-style calculator technology into the composite machine. He assisted IBM engineers coordinate input and output units with the rest of the ENIAC, for instance. It could be argued that incorporating existing technologies constituted the essence of the ENIAC, but others did not see Mauchly's role as sufficiently innovative. Nor did Mauchly help much with administrative duties.[244] It was therefore not surprising

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[240] *Honeywell*, "Findings of Fact," sections 1.1.8.6, 4.3.18, and 13.26-13.29.2. While Eckert and Mauchly's participation in the ENIAC project was self-serving, corporations helped through a sense of duty. For example, of the ENIAC project a scientist for RCA wrote, "We eagerly transmitted all the expertise we had to the Moore School. . . . There was a mood of great patriotism, everything was done for the war effort, and there were no questions asked about authorship or patent rights. A great deal of intangible and undocumented information was transmitted." Jan Rajchman, "Early Research on Computers at RCA," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 467.

[241] Douglas Robillard, Jr., "A History of the Iowa State University Research Foundation, Inc., 1938-1988," unpublished paper, Iowa State University, Ames, Iowa, circa 1988, 16.

[242] Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Alfred A. Knopf, 1978), 342.

[243] Williams did eventually get credit for two claims made in the ENIAC patent. *Honeywell*, "Findings of Fact," sections 11.5.8.1-11.5.8.2; Stern, *From ENIAC to UNIVAC*, 48. Some information comes from a letter that Stern quoted from Colonel Leslie Simon, letter to Colonel C. E. Herrstrom, 2 September 1944.

[244] Stern, *From ENIAC to UNIVAC*, 15, 38-39, and 55-57.

that others believed they contributed as much to the ENIAC and deserved equal billing on the patent. No one begrudged Mauchly's right to be acknowledged an inventor, however, because the team agreed he had supplied the underlying plan.[245]

Eckert enjoyed a different situation than Mauchly. His electronics skills commanded the admiration of everyone. Brainerd had "the highest respect for Eckert," but less for Mauchly; "he was much more of a sounding board."[246] However, Brainerd recognized that others on the team made "substantial contributions."[247] Likewise, Goldstine, who believed the ENIAC resulted from "the work of the group,"[248] gave Mauchly faint praise but described Eckert's contributions in glowing terms:

> Eckert's standards were the highest, his energies almost limitless, his ingenuity remarkable, and his intelligence extraordinary. From start to finish it was he who gave the project its integrity and ensured its success. This is of course not to say that the ENIAC development was a one-man show. It was most clearly not. But it was Eckert's omnipresence that drove everything forward at whatever cost to humans including himself.[249]

These comments sound excessive, but the team as a whole gave Eckert the most credit for the ENIAC. In fact, best evidence for a contribution by Mauchly is that Eckert was his biggest supporter. Eckert never complained about him not pulling his weight. The two men formed a partnership that lasted years. Perhaps Mauchly's ongoing contributions became manifest through Eckert. Nancy Stern, a historian of the ENIAC, considered the situation and concluded, "Eckert depended and relied upon him in an inexplicable way. Mauchly served as a catalyst for Eckert and provided a direction for the latter's genius."[250]

Genius or not, Eckert is best described as the chief engineer of the ENIAC and Mauchly as its architect. Evidence that Eckert depended on Mauchly on architectural matters comes from a series of

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[245] As an example, Robert W. Shaw was a designer of the ENIAC who believed that he should have been cited on the patent as a co-inventor. Nonetheless, in an interview with a lawyer for Honeywell, he refused to downgrade his opinion of the role Mauchly played in the development of the ENIAC. He remembered Mauchly writing reports, but he also believed that Mauchly had helped develop "the logical design for the computer." C. G. Call, of Bair, Freeman and Molinare, memorandum to D. D. Allegretti, et al., of Bair, Freeman and Molinare, 12 October 1967, p. 3. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 4).
[246] Stern, *From ENIAC to UNIVAC*, 57. Stern took the quotations from Brainerd's testimony given in the Honeywell trial.
[247] Brainerd, "Genesis of the ENIAC," 486.
[248] Testimony of Goldstine before Halladay, 868.
[249] Goldstine, *The Computer from Pascal to von Neumann*, 154.
[250] Stern, *From ENIAC to UNIVAC*, 57.

lectures that Eckert gave during summer of 1946. He reportedly did not prepare. That mattered little in lectures on electronics, but when touching on computer architecture or logic, he acted less sure.[251]

In litigation, Honeywell sought to exploit the other designers' claims of co-inventing the ENIAC. One complaint filed by Honeywell asked that the patent be ruled invalid because the others had not been credited. Judge Larson ruled otherwise, however. He agreed the project had been a team effort, and that others, including Burks, made "inventive contributions," but nonetheless concluded that Honeywell had not presented sufficient evidence on contributions by others to warrant invalidating the patent on that basis. Presented evidence indicated that not only was the conceptual design of the ENIAC largely due to Eckert and Mauchly, but that the two men, especially Eckert, functionally supervised engineering, but not the project overall. It also troubled Judge Larson that the parties alleging they had been wronged had not presented their cases years earlier.[252] The team members with strongest claims did not testify, however.[253]

It is worth adding that while the ENIAC, the machine, has received all the historical and legal attention, a significant part of the project involved how to program it. Without algorithms that could run on it, the ENIAC was of no more use than a computer is today without software. Mathematicians on the project therefore also deserve credit.

Anyway, even if not officially classified an inventor, Burks came to understand the ENIAC as one of its designers. In addition, he had overall responsibility for writing reports, including maintenance and operating manuals.[254] The tasks gave Burks a good overview of the machine. He also published several papers on the ENIAC, including the first one available to the public.[255] It is fair to characterize Burks as an authority on the ENIAC.

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[251] Martin Campbell-Kelly and Michael R. Williams, "Introduction" to *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (Cambridge, Massachusetts: MIT Press, 1985), xvii-xviii.

[252] *Honeywell*, "Findings of Fact," sections 4.2-4.3.28.

[253] Kite Sharpless and Robert Shaw were deceased by the trial. Arthur Burks agreed to testify "only to predetermined issues," to which "the Court accordingly declined." *Honeywell*, "Findings of Fact," sections 13.28-13.28.2.

[254] Goldstine, *The Computer from Pascal to von Neumann*, 200.

[255] Arthur W. Burks, "Super Electronic Computing Machine," *Electronic Industries* (July 1946), 62-67, 96. This article appeared in the edition dated July 1946 but actually published on 25 June 1946. That was one day before the critical date for the ENIAC patent application. Honeywell tried to use this fact as more evidence to have the patent invalidated for violating the patent law against publication. Judge Larson ruled against Honeywell, stating that the article did not disclose enough about the ENIAC to justify invalidating the patent. Later publications on the ENIAC by Burks described it in more detail. *Honeywell*, "Findings of Fact," sections 8.1.6-8.1.8 and 8.2.3.

As noted, Burks also became an authority on the ABC. Besides describing the ABC and its operation, *The First Electronic Computer* traced how the ABC led to the ENIAC and subsequent computers through Mauchly.[256] In their investigation, Burks and his wife, Alice, who had helped program the ENIAC, found that at least eighteen claims in the ENIAC patent derived from the ABC. These claims included the three Judge Larson cited and claim 100 to which Atanasoff took issue. The Burkses noted that many of the eighteen were general claims that apply to any digital computer. Of course, not all were, such as claim 100, which was specific. Although eighteen out of 148 claims may not seem overwhelming, the Burkses stated flatly that these eighteen claims were so vital, "that there would have been no ENIAC if Mauchly had not visited Atanasoff." The Burkses also believed that their list of eighteen claims was conservative, and numerous other claims in the ENIAC patent could be "read" in part on the work of Atanasoff and Berry. Thus, in Arthur Burks, supported by his wife, the most qualified expert confirmed the wisdom of Judge Larson's ruling.

In general terms, the Burkses cited five main areas in which Atanasoff and Berry's work had impact on the ENIAC. The first and second dealt with how Atanasoff and Berry used vacuum tubes. First, they recognized that vacuum tubes can be binary devices, and second, vacuum tubes as binary devices can be arranged into complex switching circuits. These concepts were fundamental to the ABC but were also critical to the ENIAC. Unlike a differential analyzer in which all parts were linked mechanically so that control derived naturally, the ENIAC needed extensive and sophisticated controls for all its components to operate in concert. Many controls in the ENIAC depended upon vacuum tubes arranged in the same manner as those in the ABC for performing computations, that is, as binary devices arranged into switching circuits. Eckert and Mauchly found other uses for vacuum tubes as binary devices, although they did not use them in the ENIAC in the fundamental way for computing that the ABC and subsequent true computers did.

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[256] Despite the unparalleled expertise of Arthur Burks for comparing the ABC and ENIAC, some historians of computers have suspected that he harbored resentment against Eckert and Mauchly, since he considered himself a co-inventor of the ENIAC, and thus could not be trusted to be objective. Lawyers for Honeywell thought that might be true, too, which might make him a good witness for them. Upon investigating, however, they found the opposite of what they had expected: "a very strong bias by Dr. Burks on behalf of Mauchly," an "attitude" they attributed to the men's friendship. The Honeywell lawyers therefore characterized Burks as a hostile witness and did not call him to testify. It is of great credit to Burks that he put aside that bias, investigated with an open mind, and thus found that the ENIAC did derive from the ABC. D. D. Allegretti, of Bair, Freeman and Molinare, copy of letter to Henry L. Hanson, Corporate Patent Counsel, Honeywell, 13 October 1967. ISU, Parks, "Henry L. Hanson Papers" (box 2, folder 4); see also, Nancy Stern, in Saul Rosen, "The Origins of Modern Computing," *Computing Reviews* (September 1990), 470; Nancy Stern, "Who Invented the First Electronic Digital Computer?" *Abacus* 1, no. 1 (Fall 1983), 14.

As the third major contribution of the ABC to the ENIAC, the Burkses cited the synchronized clock. Mauchly may not have liked that the ABC timed its operations with an electric motor, but he recognized the brilliance of the concept for coordinating the operations of a computer. Eckert and Mauchly substituted electronic timing in the ENIAC in place of the motor. This allowed the ENIAC to operate faster than the ABC. The downside of Mauchly's design was that he made the ENIAC exceedingly complicated and eliminated the opportunity to employ a larger memory. The Burkses believed use of modular units in the ENIAC derived from the ABC, and that constituted the fourth derivation. As the last derivation, the Burkses gave Atanasoff's method for non-restoring division.[257]

The Burkses' analysis explains why at once the ENIAC could look and operate differently from the ABC and yet be dependent on its technology. In hardware, architecture, and general operating principles, the ENIAC had little in common with the ABC. It was in timing and controls, things essential but not obvious, that the ENIAC shared kinship with the ABC. It was one thing to build an electronic computer based on the mechanical calculator and differential analyzer. It was quite another to control it. For that, Eckert and Mauchly needed the innovations of Atanasoff and Berry.

The Burkses do not mention it, but the innovation widely considered Eckert's most important, his "critical engineering insight," was use of conservative design principles. This included rigorous pre-testing of components and operating them at lower than design voltages.[258] Authorities believe that without that conservative design, the ENIAC could not have been reliable enough to succeed. Eckert no doubt contributed ideas for computer reliability, but here too, as discussed, the essential concepts came from Atanasoff and Berry. That is, Eckert's "critical engineering insight," like many of his and Mauchly's insights into computers, can be traced back to the ABC.

Thus, at the fundamental level, the ENIAC borrowed from the ABC, even if it retained none of the earlier machine's elegance. What the ABC contributed to the ENIAC is of little consequence, of course, since the ENIAC was a technological dead end. Far more important were features from the ABC that reappeared in the EDVAC and IAS computer.

It might be suspected that technologies shared by the ABC with the ENIAC, and the EDVAC, could have resulted from coincidental invention. That is unlikely for several reasons: First, Mauchly provided no evidence in court of any significant work in electronic digital devices, much less computers, before he met Atanasoff. Second, before beginning the ENIAC, Mauchly studied the

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[257] Burks, *The First Electronic Computer*, 247, 251, and 278-282.
[258] Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York City: BasicBooks, 1996), 88.

ABC carefully. It was a well-designed and nearly complete computer at the time. It was disingenuous for Mauchly to claim he learned nothing from it. Third, certain features the ENIAC shared with the ABC, such as its method of division, were based on concepts too obscure to have resulted from coincidental invention. Furthermore, the number of ENIAC patent claims that the Burkses found that read on the ABC suggests coincidental discovery cannot account for them all. Fourth, authorities close to the situation believed the ENIAC derived from the ABC. Burks has been cited, but Goldstine thought so too.[259] Unlike Burks, Goldstine helped with the project from its beginning. In fact, he was most responsible for convincing the Army to fund it.[260] Finally, Judge Larson heard and weighed all the evidence and concluded without equivocation that the ENIAC derived from the ABC.

As a closing note, Judge Larson invalidated its patent, but the ENIAC had original features. Had Eckert and Mauchly submitted the application on time, had they cited earlier inventions as appropriate, and had they been more modest in their claims, the ENIAC patent could have withstood legal challenges. So why did they overreach? It may be that they took a gamble and lost. As it were, the patent came close to dominating the industry. On the other hand, had Eckert and Mauchly applied for a patent for only their innovations, it would have had little value. The future of computers did not lie in the direction provided by the ENIAC, but rather, that of the ABC.

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[259] Goldstine, *The Computer from Pascal to von Neumann*, 125-126, 153-154, and 208.
[260] Mauchly, "Mauchly on the Trials of Building the ENIAC," 72-73.

CHAPTER 6. ADAM SMITH AND THE POPULAR VITALITY

The Atanasoff Berry Computer was a breakthrough in computing but owed its existence to private funding. It is possible that federal money found its way into the ABC, since Iowa State College received some public support. However, whatever the source of the initial money from ISC, it was not nearly enough, so Atanasoff reluctantly turned to "outside" private sources and easily obtained more money than he needed, even then in the Depression. Furthermore, importance of government monies to innovation, generally, is probably overestimated. Governments have promoted technological developments, but contrary to the prevalent impression of accelerating progress, rate of invention declined roughly coincident with that support. Other evidence suggests the quality of inventions may also have declined. Such evidence casts doubt upon the common belief that public funding of research benefits innovation and the economy.

A widespread view that sponsorship of research by government ensures economic competitiveness is fairly recent in the United States. The wise men that created the nation had appreciation for science but more for history, which suggested that republics inevitably slide into tyranny. Hoping to forestall that eventuality, the Founding Fathers affected compromises ending in a U.S. Constitution that severely constrained federal powers. It was no accident that the document permitted only negligible support of science.[1] It expressly allowed the new nation's government to "promote the progress of science and useful arts by," first, implementing a system of patents and copyrights, and second, setting "standard weights and measures" (Article I, Section 8). Worried about abuse of power, the framers of the Constitution decided money to advance science and technology beyond the two activities specified had to come from outside the central authority.

Despite slight public support for science, the young nation thrived. The United States passed a Patent Act in 1790. It did not begin efforts to standardize weights and measure until 1836, and waited until 1901 to create the National Bureau of Standards, and thus fulfilling, and likely exceeding, the limits of support allowed by the Constitution for science and technology.[2]

The variety and extent of purposes to which federal funding was put nonetheless grew steadily from the beginning of the Republic. The Louisiana Purchase by Thomas Jefferson stretched the Constitution, but he justified the scientific-oriented Lewis and Clark expedition to explore the territory under the federal government's responsibility for interstate commerce. Government paid for

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1 A. Hunter Dupree, *Science in the Federal Government: A History of Policies and Activities to 1940* (Cambridge, Massachusetts: Belknap Press, 1957), 3-6.

2 Terence Kealey, *The Economic Laws of Scientific Research* (New York: St. Martin's Press, 1996), 140.

coastal surveys for the same reason, but in 1842 the Naval Observatory had to be disguised in the budget as the Depot of Charts and Instruments to get funded.[3]

The Smithsonian Institution became the premier scientific establishment in nineteenth-century America, and it derived from private money. Englishman James Smithson died in 1829 and left 100,000 pounds sterling to the United States. Years of acrimonious debate ensued over what to do with the gift until Congress finally authorized the Institution in 1846.[4] Land-grant colleges such as ISC became centers for agricultural research, but the Morrill Act of 1862 that provided for them got approved only because Southern States, staunch defenders of states' rights, forfeited their votes in Congress during the Civil War. Also in 1862, and also due to absence of Southerners, Congress authorized the Department of Agriculture. It eventually got a large share of the federal budget for research. The latter two Congressional initiatives hint at how war has been good for public funding of science, if not probably for science itself. The National Advisory Committee on Aeronautics (NACA) and the National Research Council (NRC) were both created to help with World War I, for example, and left in existence.

Remarkable though it may seem, most people into the Great Depression probably disapproved of greater government support for science, even as they believed science beneficial. This attitude extended to scientists, as exemplified in the extreme by the nineteenth-century physicist Joseph Henry. He discovered electromagnetic induction about the same time as Michael Faraday in England. Induction is the basis of how generators, motors, transformers, and electromechanical relays operate, and therefore also the basis of manmade electrical power. Henry became the first Secretary of the Smithsonian Institution. When scientists proposed the National Academy of Sciences during the Civil War to act as an advisory body to the federal government, Henry objected. According to his strict standards, even though privately funded, such a body would be "at variance with our democratic institutions" and could be "perverted . . . to the support of partisan politics." He did become the Academy's president but refused to grovel for funding or engage in politics.[5] More generally, scientists groused as always about not having enough money, but recognized, especially at universities, that accepting federal funds meant losing freedom to choose the research they pursued

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[3] Dupree, *Science in the Federal Government*, 61-63.

[4] Thereafter, the federal government became guardian of the Smithsonian Institute and source of its operating budget. *Science Policy Study Background Report No. 1: A History of Science Policy in the United States, 1940-1985* (Washington, D.C.; U.S. Government Printing Office, 1986), 6.

[5] Joseph Henry to Louis Agassiz, letter, 13 August 1864. Quoted in Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Alfred A. Knopf, 1978), 42.

and the manner in which they conducted it. Popular belief had it that *laissez-faire* capitalism could best take care of science, innovation, and the economic health of the nation. Starting with the Menlo Park laboratory of Thomas Edison, for example, the common industrial laboratories spawned dizzying numbers of important inventions.

The Great Depression severely undercut faith in the free market and science. Many people blamed mass production for the Depression and its associated high unemployment. The problem, or so went a common explanation, stemmed from capitalistic- and science-driven industry becoming too productive.[6] Accordingly, federal monies for science were cut an average of 12.5 percent in the early 1930s.[7] Faring worse, the Department of Agriculture saw its budget chopped from $21.5 million in 1932 to $16.5 million in 1934. The Bureau of Standards budget fell by more than half: from $3.9 million in 1931 to $1.8 million in 1934.[8]

Some thought it best scientists take a holiday altogether. As one critic plaintively put it, "the physicist and the chemist seem to be traveling so fast as not to heed or care where or how or why they are going. Nor do they heed or care what misapplications are made of their discoveries."[9] Many believed that attaining a balance between production and consumption, and science and human needs, could only be accomplished through national planning, something on the model of the Soviet Union. As one, Henry A. Wallace, Secretary of Agriculture at the time, chastised engineers and scientists for being, "a handicap rather than a help," for turning, "loose upon the world new productive power without regard to the social implications." Engineers and scientists remained mired in *laissez-faire* economic thinking, he complained, when, "highly centralized forms of industrial and government control" were needed.[10]

An article in *Science* the following year, 1935, elaborated on why America needed to abandon market-oriented policies. The author conceded that under capitalism as expounded by Adam Smith in *Wealth of Nations*, published coincident with America's Declaration of Independence, "the masses of mankind attained a higher degree of material comfort and a larger measure of liberty than at any earlier time." The world had changed since 1776, however. "Social organization has become

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[6] For a full treatment of technological unemployment, see Amy Sue Bix, *Inventing Ourselves Out of Jobs?: America's Debate Over Technological Unemployment, 1929-1981* (Baltimore: John Hopkins University, 2000).
[7] Kevles, *The Physicists*, 236.
[8] Dupree, *Science in the Federal Government*, 344-346.
[9] L. Magruder Passano, "Ploughing Under the Science Crop," *Science* 81, no. 2089 (11 January 1935), 46.
[10] Henry A. Wallace, "The Social Advantages and Disadvantages of the Engineering-Scientific Approach to Civilization," *Science* 79, no. 2036 (5 January 1934), 3.

vastly more complex than it was in the eighteenth century; business planning and government planning have become closely intertwined." While attempts at national planning had usually gone awry, a notable few showed promise. The author found particularly impressive the case of Japan (already occupying Manchuria at the time). Other "constructive government planning" examples included, "the grandiose experiments of communism in Russia and of fascism in Italy." The point being, "any one who attempts to check the practise (sic) of national planning will argue in vain . . . The course of wisdom is not to oppose national planning, but to make that planning more intelligent."[11]

American engineers and scientist did tend to be conservative, but others fell naturally into the Progressive Movement as it gained momentum in the twentieth century. As a defining characteristic, progressives bristled at the freewheeling democracy and capitalism of the late nineteenth century, and as the remedy, pushed to reform society through application of expertise through government.[12] Expertise implied science, although more social science. Some progressives agreed with Wallace in finding the Soviet Union the ideal. Franklin D. Roosevelt, too, argued that the old *laissez-faire* policies were "bankrupt" and soon after becoming president in 1933 called for "a partnership in planning between government and business," enforced "by the authority of government."[13] With progressives at the helm with Roosevelt and the nation in depression, federal government rushed to create the torrent of laws, regulations, programs, and "alphabet-soup" agencies that comprised the New Deal. Likewise, in his second inaugural address, having initially slashed federal research budgets, Roosevelt turned to rational planning in science, too, and proposed that government must,

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[11] Wesley C. Mitchell, "The Social Sciences and National Planning," *Science* 81, no. 2090 (18 January 1935), 56, 59, and 61.

[12] Historian Richard Hofstadter, for one, dated the Progressive Era from about 1900 to 1914, but the term here will include most of the twentieth century because of the tendency throughout for social reform by accruing ever more power to government. The key trait of progressives, then and now, is moral imperiousness. They began as moral absolutes but became moral relativists, a distinction, Hofstadter noted, that "has sometimes been blurred because an excessively consistent practice of either leads to the same practical result—ruthlessness in political life." That is, while the point of capitalism is individual freedom, progressivism aims to force the views of the progressives on everyone. Note that progressives started calling themselves liberals by the New Deal, never mind that liberals had traditionally advocated free markets and small government and still do outside the United States. Richard Hofstadter, *The Age of Reform: From Bryan to F.D.R.* (New York: Alfred A. Knopf, 1968), 3 and 15-16; Daniel Yergin and Joseph Stanislaw, *The Commanding Heights: The Battle between Government and the Marketplace that is Remaking the Modern World* (New York: Simon and Schuster: 1998), 15.

[13] Franklin Roosevelt quoted in Yergin and Stanislaw, *The Commanding Heights*, 51-52.

create those moral controls over the services of science which are necessary to make science a useful servant instead of a ruthless master of mankind."[14]

The person most responsible for putting science under federal dominance was Vannevar Bush, and he did it by articulating massive government support for research postwar.[15] That Bush should find common ground with Roosevelt might have seemed unlikely to the casual observer in the 1930s. Bush vehemently opposed the New Deal and ardently supported *laissez-faire* economic policies. Unfortunately, he had little of the optimism typical of supporters of capitalism as espoused by Adam Smith on the intelligence and integrity of humanity. Bush, according to biographer G. Pascal Zachary, "shared with other elitists a stark and not altogether distorted view of American society that pitted sober, pragmatic elites against the untutored, volatile masses." Bush looked at people as "a blind mass (that) rushes on," "emotionally unstable," and too easily "swayed by propaganda." Sounding like a progressive, he mused darkly in 1939 that the country might need radical modification: "The totalitarian state can cut rings around the democracy, and ineffectiveness is the price of freedom . . . I wonder whether, if democracy is going to be successful, it has not got to include much more military organization of its units."

Bush's political star rose exponentially with his move to Washington, D.C., in 1939 to take charge at the Carnegie Institution. At the same time he became a member of the NACA and soon its chairman.[16] In mid-1940, Roosevelt put aside whatever political differences he had with Bush and appointed him to head the NDRC, which Bush modeled on the NACA. A year later, Roosevelt signed an executive order—most likely written by Bush—creating a more powerful civilian research management organization, the OSRD. The NDRC had been created from emergency funds available to Roosevelt. It became an operating division of the OSRD, and Bush directed both organizations. Bush continued to report directly to Roosevelt but with funding from Congress, which tended to rubberstamp his requests during the war.[17]

The NDRC and OSRD were counted great successes, although they concentrated lucrative contracts among favored organizations. MIT, associated closely with Bush, got by far the largest share among universities. Raytheon, a company Bush helped found and in which he owned stock, saw its wartime sales increase some sixty times, five times the industry average. On the whole, Bush

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[14] Franklin Roosevelt quoted in Kevles, *The Physicists*, 264.
[15] *Science Policy Study Background Report No. 1*, 24.
[16] Vannevar Bush quoted in G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: The Free Press, 1997), 64 and 95; see also 85, 98-99, 254, and 324.
[17] Kevles, *The Physicists*, 292-293 and 297-301.

deserves credit for organizing on short order the development of desperately needed weapons. With peace in sight and encouraged by Roosevelt, Bush proposed that the *ad hoc* wartime effort be replaced with a permanent government agency to give experts control over both military and civilian research. To that end, he published his famous science policy manifesto, *Science—The Endless Frontier*, calling for establishment of the National Research Foundation (NRF).[18] By then, July 1945, Harry S. Truman had assumed the presidency upon the death of Roosevelt.

Need for an NRF might be supposed to have been that Bush feared postwar science might otherwise go without funding. However, his own figures indicated that money available for research in the United States had undergone tremendous growth, even through the Depression. Between 1930 and 1940, prewar and in grips of depression and despite the early cut, and although national income fell overall, total expenditures on research and development[19] by government, both state and federal, and industry had more that doubled, climbing from $140 million to $309 million. Industrial research expenditures alone skyrocketed from $29.5 million in 1920, to $117 million in 1930, to $240 million in 1940. Furthermore, funding came from a growing number of sources, as indicated by the statistic that 288 new philanthropic foundations sprang up in the 1930s compared to 173 endowed during the prosperous 1920s. Total monies available from foundations had fallen slightly, but growth in research expenditures at universities and colleges compensated many times over. The evidence contradicts the notion that the private sector will not fund research quite generously.

Despite remarkable levels in overall research funding, particularly from private sources, Bush justified the NRF to give health-related research more money. He also wanted to continue defense research started during the war and thought government should take more responsibility for training new scientists at universities. Most important, Bush did not trust the various funding sources, left alone, to back the "pure" research he favored. According to him, research in the U.S. involved applications. Lacking was basic research to expand the "frontiers of knowledge."

Bush specifically espoused the linear model of innovation and economic development. That is, he thought scientists should be paid to conduct research without heed of applications. He claimed that such research furnished the seed from which innovation sprouted; it led inevitably to practical uses and full employment. "Basic research leads to new knowledge," he opined. "It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new

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[18] Zachary, *Endless Frontier*, 44-45, 136-137, 218-221, 226-227, and 248.

[19] Although rigorous distinction is normally made between research and development, no such care will be taken here. The two are in fact inextricably interconnected.

principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science." Bush implied that the nation had muddled through in the past by importing basic research, but because of war devastation in Europe, that was no longer an option. The U.S. therefore had to shoulder the burden of basic research but lacked a national science policy and the coordinating agency he thought essential.[20]

It may be too much to say that Bush intentionally misinformed the public, but *Science—The Endless Frontier* hardly squared with the evidence. Objectivity was beside the point, however. As Zachary put it, Bush wanted his report to annunciate a "fable," to "become a kind of creation myth, a founding story about the new world conceived by the union of science and government."[21]

The report received widespread approval from those who accepted the linear model of innovation and equated the performance of the OSRD with that anticipated from a NRF. Unlike the stated primary purpose of the NRF, however, the OSRD and the military had not attempted basic research. They assigned projects with a reasonable chance of completion in a short time. Thus, OSRD projects built upon research and development accomplished before the war. Financed by the Army, the ENIAC was otherwise no exception. The atomic bomb was the most daring of wartime projects, but even it derived from extensive prewar research in nuclear physics, notably the first man-induced atomic fission in 1938 by Otto Hahn and Fritz Strassman in Germany, but including studies conducted with numerous cyclotrons in operation beginning in the early1930s.

Such major breakthroughs as jet engines, rockets, DDT, and penicillin, all supposed triumphs of government-sponsored, war-related invention actually came before the war. Several inventors independently designed turbojet engines by the mid-1930s. Among them, for example, Frank Whittle, a Royal Air Force officer, turned to the British Thomason-Houston Company, and not the British Government, to build an engine in 1937.[22] American Robert Goddard began launching liquid-powered rockets in the mid-1920s with funding from the Research Corporation and Guggenheim Foundation. DDT was first synthesized in 1874, and Paul Müller, of the J.R. Geigy Chemical Company in Switzerland, found it to be an insecticide in 1939. DDT saved the health and lives of millions, as did penicillin. The OSRD oversaw the first large-scale production of penicillin by drug

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[20] Vannevar Bush, *Science—The Endless Frontier* (Washington, D.C.: Government Printing Office, 1945), 1-3, 6-7, 13-14, and 17. Some information is from, "Table I Scientific Research Expenditures and National Income," 80; Kevles, *The Physicists*, 267. For numbers of foundations endowed, see footnote 1.

[21] Vannevar Bush quoted in Zachary, *Endless Frontier*, 222-223.

[22] Edward W. Constant II, "A Model for Technological Change Applied to the Turbojet Revolution," *Technology and Culture* 14, no. 4 (October 1973), 562-565.

corporations, but Alexander Fleming, Howard Florey, and Ernst Chain discovered and developed penicillin in Great Britain sponsored largely by the Rockefeller Foundation.[23]

Bush and scientists had little incentive to correct the popular miscomprehension. Rather, they basked in the windfall of adulation and public money now streaming their way. Nor did they care to admit that, as far as technology contributed to winning the war, the great share of credit should go to the private sector. Not only had it accomplished most of the applied and basic research attributed to government, but also American industry produced fully half the world's manufactured output and more than the combined total of the Axis countries. As a sample, the U.S. during World War II produced some 300,000 military airplanes, 86,000 tanks, and 6,000,000 tons of bombs. By 1945, American shipbuilders were launching a new cargo ship every day. The unleashed manufacturing might of the United States was truly awesome.[24]

Moreover, while Bush was right that Americans had historically focused on applications, that lopsided emphasis began changing before the war, partly because of the numbers of ambitious people entering science. For example, universities in the United States granted thirty-one Ph.D. degrees in physics in 1920. Ten years later, 105 physics doctorates graduated with Atanasoff. The trend continued steadily upward, never mind the Depression, peaking at 186 in 1941, and then falling precipitously with onset of war. Only forty-three physics Ph.D. degrees were awarded in 1945.[25] Furthermore, many scientists from Europe settled in the U.S. in the 1930s. Over one hundred physicists had emigrated by 1941, including von Neumann, Teller, and Einstein. Some scientists came to escape growing political turmoil in Europe, but others simply wanted to partake of the wealth of money available in America, even though the Depression hit harder overall in the U.S. than Europe. By 1940, physics research in America clearly stood head-and-shoulders above that anywhere. Bush conceded the same was true in medicine. As one indication of the improved quality, Americans begin winning or sharing Nobel Prizes at an increasing rate, including seven in medicine, two in chemistry, and four in physics during the 1930s alone.

Scientific advancements came because of the quality of practitioners and because private sources sponsored research unstintingly. Already by 1936, long before ISC got its government-funded synchrotron, the U.S. had more cyclotrons or related nuclear accelerators than all the rest of the world, and all privately funded.[26] Nor had sources held back in contributions to public health.

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[23] Fleming, Florey, and Chain shared the Nobel Prize in medicine in 1945; Müller won it in 1948.
[24] Zachary, *Endless Frontier*, 224-225.
[25] L. R. Harmon, "Physics PhD's: Whence, Whither, When?" *Physics Today* 15, no. 10 (October 1962), 21.
[26] Kevles, *The Physicists*, 281-283; Bush, *Science—The Endless Frontier*, 10.

Indeed, funding such research had become a hot area. Frank Jewett, a loyal supporter of Bush but clinging to an idea of scientific integrity and independence already old fashioned, noted rightly that it was "easy" to raise money "from a willing public in connection with any one of a number of specific diseases."[27] In short, basic research thrived in the U.S., as nowhere else, even before the war.

Careful choice of words is crucial to spinning a successful fable, and the language in *Science—The Endless Frontier* bordered on the disingenuous. Bush wrote in elegant and elevated prose of honored traditions he proposed to continue in science, as exemplified by the following passage:

> It has been basic United States policy that Government should foster the opening of new frontiers. It opened the seas to clipper ships and furnished land for pioneers. Although these frontiers have more or less disappeared, the frontier of science remains. It is in keeping with the American tradition—one which has made the United States great—that new frontiers shall be made accessible for development by all American citizens.[28]

Bush's reassuring diction provided cover for what was in truth a break with the American past. He wanted to restrict the frontier of science to the select few, ignoring the fact that land on the frontier of the American West had been open to most, if not all, takers, who had pushed westward regardless of hardship or what government did.

Bush slanted history because he thought it imperative that science and the nation be protected from that "blind mass" whose courageous and resourceful ancestors settled America, but who he and progressives believed incapable of acting responsibly. Bush accordingly advocated, "a rigidity of control and a pyramidal system for the operation of the entire effort."[29] Thus, government sponsorship had less to do with better science and more with its control. On the other hand, what served for others did not for him. With the talk of prewar progressives still weighing on his mind, Bush worried, "whether science in this country is going to be supported or whether it is also going to be controlled."[30] That is, he wanted scientists free of government tentacles. He thought government should impose taxes on people to transfer to the NRF, no strings attached. Scientists, actually an elite cohort, would ultimately control research largely independent of accountability, including the president. To build his aristocracy of scientists, Bush asked for a budget to reach $122.5 million annually in five years.[31]

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[27] Zachary, *Endless Frontier*, 252-253.

[28] Bush, *Science—The Endless Frontier*, 6.

[29] Vannevar Bush quoted in Zachary, *Endless Frontier*, 226-227.

[30] Vannevar Bush quoted in Kevles, *The Physicists*, 347, footnote 8; Zachary, *Endless Frontier*, 8.

[31] Bush, *Science—The Endless Frontier*, 28-33.

That science needed government funding now had broad agreement, although many held strongly opposing ideas on a program structure, some ostensibly more democratic. For example, one bureaucrat argued in response to Bush: "Let us all bear in mind that we have a political Government and that our Constitution is a political instrument. The political character of our Government guarantees democracy and freedom, in which the people, through their Government, decide what they want."[32] A key phrase was "through their Government." Democracy and freedom now meant something quite different than in Henry's day, when self-reliant people made do with minimal state assistance. Progressives envisioned democracy as citizens voting for the officials who would oversee the machinery to restrain them, the people. Progressives might argue over who among them should hold what powers, but agreed in expanding governmental bureaucracy to take greater responsibility for American life, even as they endeavored to give more Americans more direct say in government.

In similar vein, Western nations in the 1930s became "mixed economies," in which governments came into dominating roles. However, Americans proved more recalcitrant than Europeans in accepting that change. For instance, early in his administration, Roosevelt attempted to implement his "partnership in planning between government and business" through a major new organization called the National Recovery Administration (NRA). It was to work in concert with industry to solve the imagined problem of overproduction by reducing output and setting prices. Americans did not trust business and government in such intimate relationship, however, and the Supreme Court ruled the NRA unconstitutional. Roosevelt created numerous other agencies and regulations that survived, but a bad experience with rationing and other wartime economic policies, in particular, made Americans wary of further expansions of federal government.[33] In the case of science, however, many found Bush's linear economic model compelling, particularly because they feared losing the Cold War. The USSR reportedly had spent the equivalent of $200 million a year on science as early as the mid-1930s.[34]

Thus, out of the postwar political process fell a haphazard science policy with funding coming from diverse sources within government. Bush by no means got all he otherwise wanted. His insistence that the NRF be largely free of the president's influence caused Truman to balk, as one obstacle.[35] Congress finally approved the National Science Foundation (NSF) in 1950, but with a

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[32] Maury Maverick, head of the Smaller War Plants Administration, October 1945, quoted in Kevles, *The Physicists*, 348.
[33] Yergin and Stanislaw, *The Commanding Heights*, 12, 21-38, 51-52, and 56.
[34] Kevles, *The Physicists*, 336-337.
[35] William A. Blanpied, "Inventing US Science Policy," *Physics Today* 51, no. 2 (February 1998), 34-40; Kevles, *The Physicists*, 357 and 365-366.

more restricted purview and greater accountability than Bush envisioned. Moreover, the NSF got about one-tenth the money he had anticipated.[36] Even so, there emerged by the early 1950s what historian Daniel Kevles called a "victory for elitism," a "revolution" in America in which scientists (actually physicists, with physics being the elite science) wielded considerable political power.[37]

If the NSF failed to become what Bush had hoped, overall federal spending on research nonetheless mushroomed. It dropped off slightly after World War II but soon jumped sharply thanks to heating of the Cold War. The October 1957 launching by the Soviet Union of *Sputnik*, first artificial satellite, really propelled science-related funding into orbit in the U.S. If not enough that the economy of the USSR outpaced those of Western nations, or so many thought, the communists also seemed to be outstripping everybody else in innovation. President Dwight Eisenhower warned that the Soviet Union had more scientists and engineers than the U.S. and was widening its lead every year. The virtue of state management seemed increasingly clear; the question was no longer should governments guide the markets, but specific means to use. Few now disagreed that Bush had the right idea: Inventions derived from basic research, which had gotten too expensive and risky for the private sector to manage. Government through its agencies should fund basic research, some applied research, and even development, in good part for defense, but also for long-term economic welfare, because industry could commercialize discoveries. This arrangement ensured both ongoing national security and prosperity. The concept remains entrenched to this day.[38]

Federal government provided less than 20 percent of total expenditures for research in the 1930s, and most years less. The low was 12 percent in 1934. It averaged 83 percent of total during World War II, about $600 million per year. Percentage of research sponsored by federal government dropped to around 54 percent by the early 1950s, even as amounts increased steadily to $625 million in 1947 and to $2.8 billion in 1953 with the Korean War. By 1961, after *Sputnik*, spending by federal government on research rocketed to $9.3 billion, 64 percent of total.[39] Public support for science as a percentage of total spending then decreased after the 1969 moon landing. Federal contribution stood at 57 percent of total at 1970. By 1980, federal government funding of research had fallen to 47 percent of total, and in 1995 to 35.5 percent. Nonetheless, corresponding amounts of federal funding

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[36] Kealey, *The Economic Laws of Scientific Research*, 150-156.
[37] Kevles, *The Physicists*, 365-366.
[38] Bruce L. R. Smith, *American Science Policy since World War II* (Washington, D.C.: Brookings Institution, 1990), 1-37; Kevles, *The Physicists*, 384.
[39] Kenneth Flamm, *Targeting the Computer: Governmental Support and International Competition* (Washington, D.C.: Brookings Institution, 1987), 7. See, "Table 1-3. U.S. Expenditures on Research and Development by Source of Funds, Selected Years, 1930-61."

continued climbing steeply, from $14.9 billion in 1970, to $29.5 billion in 1980, to $60.7 billion in 1995. This indicates that while federal funding has grown dramatically, private research has increased more. Incidentally, of 1995 federal funding, 28.1 percent went for basic research, 23.7 percent went for applied research, and the rest to development.[40]

Although Americans still believe government oversight of science essential to the welfare of their nation, it is now possible to measure promise against performance, which has been none too encouraging. For example, did the tidal wave of public money result in a similar upswell in patents? It did not. A high water mark for issued patents was 53,458 in 1932. Because of several years delay normal before an application is granted, most of the applications probably had been submitted before the Depression. Numbers of patents ebbed until 1937, with 37,683 patents granted that year, and then recovery began. With the war, however, patents went into freefall, to a low of 20,139 in 1947; this despite the federal government allowing private citizens to take out patents on inventions made with public funds. Not only did Eckert and Mauchly patent the ENIAC, for example, but also Atanasoff patented a sweep for destroying pressure mines. War is said to be a fount of innovation, but the opposite is actually true. The tide in patents started upward again but took until 1965 for those granted to finally exceed that of 1932. Actually, the trend in growth of patent applications by Americans has probably never matched that prewar.[41] Thus, as far as numbers of patents measure innovation, government intervention appears to have been an abject failure.

Neither is there evidence that inventions are any better. The National Academy of Engineering ranked what it considered the greatest engineering achievements of the twentieth century based on impact on quality of life. The top ten achievements are attributable primarily to inventions made before widespread state involvement.[42] Economist Robert J. Gordon went further to note that a disproportionate number of fundamental inventions, what he called the "Great Inventions," came in

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[40] National Science Board, *Science and Engineering Indicators—1996*. See, "Appendix Table 4-4: National Expenditures for Total R & D, by Source of Funds and Performer: 1970-95," 107. See also corresponding tables for basic and applied research and development, 108-110.

[41] Patent figures were taken from the United States Patent Office web site and include only domestic patents referred to as "patents for inventions." Economists warn that patent statistics are difficult to interpret. Zvi Griliches, for example, believed something changed in what patents measure. Zvi Griliches, "Patent Statistics as Economic Indicators: A Survey," in *R&D and Productivity: The Econometric Evidence* (Chicago: University of Chicago Press, 1998), 287-300 and 322-336. See, in particular, "Fig. 13.9 Patent applications by U.S. residents and real GNP and investment, 1880-1989, log scale," 329.

[42] The National Academy of Engineering ranked the top ten engineering achievements of the twentieth century as electrification, automobile, airplane, water supply and distribution, electronics, radio and television, agricultural mechanization, computers, telephone, and air conditioning.

the second half of the nineteenth century. The immediate predecessors to the computer were invented then, of course, but just one decade or so, 1876 to 1886, saw inventions of the electric light, electric transformer, steam turbine generator, internal combustion engine, automobile, reinforced concrete, skyscraper, refrigerator, telephone, phonograph, fountain pen, theory of vaccines, indoor flush toilet, and more, including the cathode ray tube and Nipkow scanning disk, another precursor to television.[43] Other decades in the late nineteenth century were almost as astoundingly fecund.

The greatest inventor of the age, or of any age, Edison, was considered "addled" as a child and had only three months formal schooling but accumulated 1,093 patents. Edison insisted he created through hard work and common sense, not genius. Nor did he need government handouts. On the other hand, in 1898 the Army gave $50,000 to the head of the Smithsonian Institution, Samuel Langley, to develop an airplane, but it took two bicycle mechanics from Ohio, Orville and Wilbur Wright, working without such largess, to make one that flew.[44] The plethora of great and privately funded inventions of over a century ago formed the very basis of modernity, transforming, noted Gordon, "often abysmal living conditions to today's much easier and more pleasant life." As one happy consequence, life expectancy in America rose 0.72 percent per year from 1900 to 1950.

As another consequence, the great inventions of the last decades of the nineteenth century ushered in productivity increases that more than doubled the already unprecedented figures of the century as a whole, and that lasted through much of the next century, but highlighted by progressives as a cause of the Depression. If the period was a golden age of invention that instigated a golden age of productivity and standards of living improvements, it is fair to note that the late nineteenth century was also a golden age of *laissez-faire* capitalism. Historians disparage the 1870s to 1890s, or so, as the "Gilded Age"[45] because of immense wealth amassed by a few, but an outfall of the rambunctious but creative era has been more prosperous lives for the vast majority of people.[46] Moreover, some

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[43] The list of inventions here is taken from Bryan H. Bunch and Alexander Hellemans, *The Timetables of Technology: A Chronology of the Most Important People and Events in the History of Technology* (New York City: Simon & Schuster, 1993).
[44] Alan I Marcus and Howard P. Segal, *Technology in America: A Brief History*, 2nd. ed. (New York City: Harcourt Brace College Publishers, 1999), 201-202.
[45] The term "Gilded Age" came originally from a novel of that title by Mark Twain and Charles Dudley Warner.
[46] As an aside, it is assumed that, in articulating a "struggle for existence" as a prime mover within his theory of evolution by natural selection, Charles Darwin was influenced by nineteenth-century capitalism. Karl Marx, impressed with Darwin's theory, was one of the first to make that connection explicit. Struggle for existence escalated into the more brutal phrase "survival of the fittest" thereafter associated with cutthroat capitalism. In fact, before Darwin, economists generally thought that capitalism benefited all participants, although some people do better than others. Even Thomas Malthus, gloomiest of the early economic philosophers and who used the phrase struggle for

personages of wealth, such as John D. Rockefeller and Andrew Carnegie, founded great philanthropic organizations. Unfortunately, productivity improvements lost steam approximately in step with the steadily increasing role of government. By 1972, productivity growth rates had ground down significantly. Increases in life expectancy also slowed considerably.

Productivity has evidently improved lately, and some analysts attribute that to the computer. However, Gordon concluded that any productivity improvement has been in fact narrowly limited to computers and related equipment and not shared by the 88 percent of the economy beyond durable manufacturing, although the service sector has made great use of computers. Moreover, in his analysis, the computer and Internet have not matched the contributions of the great inventions of the nineteenth century. To anyone who doubted that, Gordon asked them to consider whether they would rather give up the Internet or indoor plumbing. It is possible that computers and the Internet will gain new significance, of course. However, Gordon pointed out that the marginal utility of computers appears to be declining, hinting that its greatest contribution is past. Consider, for example, that the first word processing software packages were a big improvement over typewriters, but subsequent packages have consistently offered less gain in marginal effectiveness, even as computers have grown in power exponentially.[47]

If there has been no evident improvement in innovation with government intervention, neither is there a clear rise in quality of basic research. There seems to have been no new theories in physics matching the impact of relativity or quantum mechanics, for example. A discovery that came as close as any also occurred before the war and resulted from private money. American Edwin Hubble used the 100-inch Hooker telescope at the Mount Wilson observatory to observe in patterns of heavenly light that the universe is, for all practical purposes, infinite but expanding. The Wilson observatory owed its existence to the Carnegie Institute and the Hooker telescope to a gift from a businessman.

Perhaps the most beneficial research of the last century was that represented by Wallace breeding hybrid corn, based partially on government-funded research. However, just before taking office as vice president in 1941, Wallace visited Mexico. Upon return, he asked the Rockefeller Foundation if it might do something to alleviate subsistence conditions common there. Led by

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existence and whom Darwin cited as an influence, believed competition served to help the poor live better lives, not drive them further into poverty. Peter J. Bowler, *Evolution: The History of an Idea* (Los Angeles: University of California Press, 1989), 19, 99-103, 107-108, and 172-173.

[47] Robert J. Gordon, "Does the 'New Economy' Measure Up to the Great Inventions of the Past?" *Journal of Economic Perspectives*, 14, no. 4 (Fall 2000), 49-74. See, in particular, "Table I. Growth Rates of Output, Inputs, and Multifactor Productivity, Selected Intervals, 1870-1999," 53.

officials including Warren Weaver and J. George Harrar, the foundation funded research by Norman Borlaug and others that, in a "green revolution," yielded superior varieties of corn, rice, and wheat that kept an estimated one billion people worldwide from starvation.[48] As far as scientific research has served humane purposes, arguably more credit must go to Rockefeller and Carnegie than Uncle Sam, even if federal government spent more money.

Finally, did money the government put into research at least improve the defense of the United States? Again, the answer is perhaps not. In the late 1960s, the Department of Defense commissioned Project Hindsight to investigate what it had gotten for its estimated $10 billion spent on basic research since World War II. The study concluded that the great majority of new weapons emerged from preexisting technologies and not from scientific breakthroughs.[49] What had been true during the war continued to be true.

Eisenhower more than any modern president retained a sense of restraint and balance toward public support of science. In his presidential "Farewell Address," he famously warned of the dangers posed by an unregulated "military-industrial complex," even as he believed the Cold War made that alliance necessary. However, rarely noted is that in the same speech he also emphasized that "public policy could itself become captive of a scientific-technological elite," subverting the nation's democratic processes. Furthermore, the other side of that problem, according to Eisenhower, was that the "prospect of domination of the nation's scholars by Federal Government, project allocations, and the power of money is ever present—and is gravely to be regarded." Moreover, because of lavish spending on research by government, "a government contract becomes virtually a substitute for intellectual curiosity."[50] In short, just as the Founding Fathers feared concentration of power, a danger was that scientists could come to control public policy, dispense money generously to themselves, but not do enough to earn it, while placing democracy in jeopardy.

In summary, if public financing of research may have yielded new technologies, perhaps even a few possible no other way, it is doubtful the nation is better off as a result. Rather, there may

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[48] Warren Weaver, *Scene of Change: A Lifetime in American Science* (New York: Charles Scribner's Sons, 1970), 94-104; John C. Culver and John Hyde, *American Dreamer: The Live and Times of Henry A. Wallace* (New York: W. W. Norton, 2000), 247-251.

[49] Concerned about the implications of Project Hindsight, the National Science Foundation commissioned its own study, Project TRACES, to review the conclusions of Hindsight. It claimed that Hindsight was mistaken and basic research was fundamental for new weapons. *Science Policy Study Background Report No. 1*, 59-61.

[50] Dwight D. Eisenhower, "Farewell Radio and Television Address to the American People," 17 January 1961, in *Public Papers of the Presidents of the United States: Dwight D. Eisenhower, 1960-61* (Washington, D.C.: U.S. Government Printing Office, 1961), 1,038-1,039.

have been a net lose, considering the apparent slowing of progress. Note that, despite continual promises by scientists of a marvelous new world lying just ahead due to their efforts and government funding, the essential technologies of the twenty-first century remain mostly those invented before World War II. It may be that state financing has made life easier for scientists, but that should not impress taxpayers, forced to give up hard-earned wages to pay for it.

Science and technology flourished before the federal government got involved to any great degree. They did so well in the days of little or no income taxes, in fact, that many people believed their very fruitfulness behind the Depression. After World War II, however, advocates for big government, including now scientists, insisted that not only the more science the better but also that research had become so expensive that only a powerful state could afford it. However, if true that the private sector would no longer back research sufficiently, then computers, as a high-tech product, ought to provide evidence. Yet even superficial examination of the evolution of computers casts doubt on need for public assistance. The fundamental advances occurred before the war, and with the examples of the ABC and similar machines, a von Neumann-type computer certainly would have resulted as industry regained its stride after being sidetracked in defense projects. Recall that IBM gladly funded the ASCC and other expensive machines, but put aside related research to help with the war. Then, von Neumann deliberately snubbed industry for the IAS computer. Furthermore, of the four major innovations in computing technology after the computer itself, that is, transistors, integrated circuits, rotating magnetic memory, and magnetic core memory, government's contribution to all has been overstated.

As discussed, research into solid-state devices began long before World War II and before quantum mechanics could satisfactorily explain them. Semiconductors actually became objects of scientific curiosity a century earlier, beginning with Faraday's discovery in 1833 that conductivity and temperature of silver sulfide are directly related. Most metals have the opposite characteristic: conductivities go up as temperature goes down. Several years later, Frenchman Alexander-Edmond Becquerel found that a voltage resulted when light impinged on the point where a semiconductor and electrolyte met. This was the phenomenon Einstein explained as the photoelectric effect. Uses for semiconductors did not wait, however. A notable example was the "cat's whisker" rectifier for detecting signals in early crude radios. It consisted of a metal wire touched against a crystal of galena (lead sulfide) or pyrite (iron sulfide). Interest in the unreliable cat's whisker rectifier waned with Fleming's invention of the vacuum-tube diode.[51]

Theoretical explanation for semiconductors came several years after the Copenhagen interpretation of quantum mechanics. In 1931, after explaining the difference between conductors and insulators at the atomic level, British physicist Alan H. Wilson expanded his theory to include semiconductors. It was understood by the war that semiconductors are typically elements in the fourth column of the periodic chart and neither good conductors nor insulators in pure form. Semiconductors become conductors when combined with elements from the third or fifth columns. In the 1930s, before scientific details could be ironed out, mass manufacture of rugged diodes began from plates of copper oxidized on one side.[52] Julius E. Lilienfeld, a German émigré, earlier experimented with an amplifier made from copper sulfide. In Germany, Oskar Heil designed a triode consisting of copper oxide, vanadium pentoxide, tellurium, and iodine. R. W. Pohl, another German, created an amplifier from a potassium bromide crystal in 1938. At the BTL the next year, William Shockley suggested an amplifier using copper oxide.

The BTL largely put aside its substantial efforts in semiconductors during the war. Shockley and Walter Brattain got pulled into various defense activities. John Bardeen helped with mine research at the NOL. The federal government did not sponsor research into transistors but continued that into germanium diodes.[53] Such diodes performed combinational logic in computers after the ENIAC. Numbers of fragile and power-hungry vacuum tubes could thus be greatly reduced, particularly since one diode could often replace multiple vacuum tubes.[54]

Transistors eventually replaced the rest of the tubes, of course, but it took the BTL several years after the war to regain momentum and create the first crude transistors, quite independent of government. While government paid 25 percent of the transistor's subsequent development costs through the 1950s, that still left the great share to the BTL. Had government not provided its fraction of support, the BTL would have continued development of transistors for the simple reason that it needed them.[55] It might have taken a little longer to perfect their manufacture, but that was unlikely to have made much difference to consumers, since the military monopolized production for the first

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[51] Editors of *Electronics, An Age of Innovation: The World of Electronics 1930-2000* (McGraw-Hill, 1981), 66.
[52] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W. W. Norton, 1997), 65-68, 90-92, and 97-98.
[53] Editors of *Electronics, An Age of Innovation*, 26 and 67-71.
[54] Charles J. Bashe, et al., *IBM's Early Computers* (Cambridge, Massachusetts: MIT Press, 1986), 118-119.
[55] Riordan and Hoddeson, *Crystal Fire*, 116.

years.[56] Much the same story occurred with integrated circuits. Public funding contributed nothing to the invention of integrated circuits but helped with their continued development. Industry certainly would otherwise have shouldered the burden by itself. Government's greatest contribution was providing a market in the early years before manufacturing techniques became perfected.

Government sponsored development of rotating magnetic storage mechanisms by ERA, but similar devices had been proposed before the war, including by Atanasoff and Bush. The Germans during the war recorded sound on plastic tape coated with iron oxide.[57] Also in Germany, Gerhard Dirks designed electronic computing machines that included magnetic storage. After he won a patent for a rotating magnetic storage drum with a clock track, it was inexplicably revoked. The German Patent Office deemed the mechanism not sufficiently inventive.[58] In 1946, Andrew Booth, at the University of London, proposed a number of magnetic storage devices, including disc.[59] IBM began work on magnetic-disc storage in 1949, although it used that by ERA instead.[60] In summary, rotating magnetic storage was a common concept posing no inordinate developmental obstacles.

Magnetic core storage deserves greater elaboration. Historians of computers attribute it and other technologies, including timesharing, computer graphics, and certain reliability mechanisms, to the Whirlwind computer project. Whirlwind is also interesting because better records were kept on it than most projects, and they provide a cautionary tale of the waste that can result when scientists have free reign and unlimited budgets.

Whirlwind began relatively modestly in 1944 as a flight simulator called ASCA[61] to train naval bomber pilots. The Navy preferred giving the project to the BTL but asked MIT to do a preliminary investigation, in part because it anticipated the school could do it cheaper. MIT assigned ASCA to Jay W. Forrester, a graduate student in electrical engineering and associated with the school's Servomechanisms Laboratory. Forrester proposed a training cockpit controlled by analog mechanisms that could compute, among other things, the thirty-three simultaneous equations needed

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[56] Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988), 16.
[57] Bashe, et al., *IBM's Early Computers*, 188.
[58] Konrad Zuse, *The Computer—My Life*, trans. Patricia McKenna and J. Andrews Ross (New York: Springer-Verlag, 1993), 106, 107, and 111.
[59] Andrew D. Booth, "Computers in the University of London, 1945-1962," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 553.
[60] Emerson W. Pugh, *Building IBM: Shaping an Industry and its Technology* (Cambridge, Massachusetts: MIT Press, 1995), 168 and 178-179.
[61] ASCA is an acronym for Airplane Stability and Control Analyzer.

to mimic the responses of an airplane in flight. MIT estimated a prototype could be built in one year for $200,000. Wary, the Navy asked for further study, and by mid-1945, MIT recognized that building a simulator was significantly more difficult than originally thought. It negotiated a contract to give it $875,000 and eighteen months to complete the job. About then, Perry Crawford and Samuel Caldwell urged Forrester to consider digital controls.[62]

Caldwell independently planned to reactivate the Arithmetical Machine, the project the Center of Analysis had started before the war with funding from NCR. Then, with World War II over, Caldwell returned to MIT. Weaver, his boss at the NDRC, went back to his former job. After Weaver showed him an application von Neumann submitted to the Rockefeller Foundation for funding what became the IAS computer, Caldwell claimed the Arithmetical Machine had greater potential, at least in certain aspects. Like von Neumann, Caldwell emphasized applied mathematics, stating: "There is a strong feeling that mathematics is entering a period of great new accomplishment by way of the mass production of numerical solutions, and we are potentially situated to operate among the leaders in that advance." MIT followed up with a formal request for funding and a promise that Norbert Weiner would thenceforth be closely associated with the Arithmetical Machine. Caldwell thus got $100,000 from the Rockefeller Foundation and von Neumann got nothing.[63]

Meanwhile, Forrester learned of the ENIAC and EDVAC projects, the former nearing completion and the latter under consideration. By January 1946, Forrester and his partner, Robert Everett, agreed that flight simulation was too complex for analog mechanisms alone, so they added a digital computer to the project. MIT accordingly renegotiated its contract to give it until June 1950 to deliver a simulator at the hugely increased price of $2,434,000. MIT also changed the name of the project to Whirlwind.

The Navy still wanted a simulator, but as the name change hinted, Forrester and the youthful design team he assembled decided to focus on a general-purpose digital computer capable of operating in real time. As two historians of the project aptly put it: "the tail had passed through and beyond the point of wagging the dog and had become the dog." If that means the cockpit became the tail, then it got chopped off. The Whirlwind team deferred the cockpit and devoted all efforts to the computer. Worse, Forrester had a cavalier attitude toward expenditures. He believed Whirlwind worth whatever it cost and spent as if he had no limit. One critic complained the project employed,

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[62] Kent C. Redmond and Thomas M. Smith, *Project Whirlwind: The History of a Pioneer Computer* (Bedford, Massachusetts: Digital Press, 1980), 1-2, 5-6, 12-16, and 22-23.
[63] Samuel H. Caldwell, report to Warren Weaver, excerpts quoted in Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882-1982* (Cambridge, Massachusetts: MIT Press, 1985), 232-234.

"hot and cold running secretaries." The Navy watched the transformation of ASCA with growing anxiety and might have canceled the project if not for the political clout of MIT. Meanwhile, Crawford left MIT to head the Navy division responsible for Whirlwind, and he championed the project as an insider.

Adding to the discord was confusion over the design of Whirlwind. It began something like the EDVAC. It became more like the IAS computer, including parallel transmission of data and, for a time, cathode ray tube memories.[64] As it were, MIT had two computer projects proceeding along roughly similar paths. However, with so much money being sucked into Whirlwind, the Arithmetical Machine could not compete, and MIT discontinued it in 1947.[65] Critics compared Whirlwind unfavorably to the IAS computer and Arithmetical Machine, questioning why it cost so much more. Forrester responded, with some merit, that criteria for his machine were more demanding. Whirlwind needed to be faster and more reliable to control a simulator in real time. Actually, the simulator was all but forgotten, but to justify his project and keep money coming in, Forrester began promoting Whirlwind as the center of a large information system for military applications with an estimated cost of $2 billion.

Grandiose thinking became key to Whirlwind's ultimate success. The Navy finally had enough and extracted itself as best it could from project obligations, although in return, it had to establish a new center at MIT for machine computation and numerical analysis.[66] Fortunately for Whirlwind, the Cold War intensified in the knick of time. The Soviet Union exploded its first atomic weapon in August 1949, and the next year the Korean War began. The Air Force worried that the nation urgently needed protection against long-range bomber attack. It therefore took over much of the funding for Whirlwind, intending it to be part of development of an early warning system of radar installations and computers called SAGE.[67] Forrester thus finished Whirlwind in 1951. It contained about 4,200 vacuum tubes [68] and cost as much as $5 million, making it by far the most expensive of the early computers. Whirlwind became the computer for the Cape Cod system, the prototype to SAGE.[69] Forrester and the Air Force then selected IBM to develop and build computers for SAGE,

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[64] Robert R. Everett, "Whirlwind," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 366-367.
[65] Karl T. Compton, President, MIT, letter to Warren Weaver, 25 June 1947, quoted in Wildes and Lindgren, *A Century of Electrical Engineering and Computer Science at MIT*, 235.
[66] Wildes and Lindgren, *A Century of Electrical Engineering and Computer Science at MIT*, 293.
[67] SAGE is an acronym for Semiautomatic Ground Environment.
[68] Redmond and Smith, *Project Whirlwind*, 25-27, 41-43, 46, 69, 116-117, 131, and 138.
[69] Everett, "Whirlwind," 377.

twenty-six mammoth AN/FSQ-7 and AN/FSQ-8 computers, each actually two machines operated in tandem for reliability.[70] Estimates of SAGE's cost range from $4 billion to $12 billion.

The stated lesson of Whirlwind has been that public funding of science, no matter its purpose or how extravagant, is always worthwhile. Whirlwind did seem serendipitously to fill a critical military need. However, ballistic missiles had become the major threat by completion of SAGE. Timely detection of missiles or newer airplanes was beyond its capabilities. Thus, the United States built another system, the Ballistic Missile Early Warning System (BMEWS), to detect those threats.[71]

It is also true that by 1952 Forrester gave Whirlwind a magnetic core memory capacity of 2,048 sixteen-bit words.[72] Others invented magnetic core memory simultaneously, however. Mauchly claimed that he and Eckert discussed it as they designed the ENIAC, making theirs the earliest consideration if true.[73] IBM began considering core memory as early as 1946. It hired Munro K. Haynes after he completed a dissertation in 1950 entitled, "Magnetic Cores as Elements of Digital Computing Systems."[74] He helped fabricate a prototype in 1952.[75] In Great Britain, Booth proposed core memory in 1947.[76] Ralph Slutz and Richard Snyder independently applied for a patent on it that same year. The two men helped with the IAS computer, but its project team made speed of implementation a higher priority and chose to stay with cathode ray tubes.[77] At RCA, Jan Rajchman successfully implemented iron core memory in 1952.[78] Whatever its benefit to defense, Whirlwind was not essential to invention of magnetic core memory.[79] Moreover, private interests doubtlessly would have independently developed all the mechanisms associated with Whirlwind.[80]

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[70] Pugh, *Building IBM*, 215.
[71] Editors of *Electronics*, *An Age of Innovation*, 99.
[72] Flamm, *Creating the Computer*, 58 and 88-90. See also, "Table 3-1. Early U.S. Support for Computers," 76-77; David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware / Software Interface* (San Francisco: Morgan Kaufmann, 1994), 522-523.
[73] *Sperry Rand Corporation v. Control Data Corporation*, United States District Court, District of Maryland, Civil Actions Nos. 15,823-15,824, "Deposition of John W. Mauchly," 210-215. ISU, Parks, "John Vincent Atanasoff Papers" (box 19).
[74] Pugh, *Building IBM*, 209.
[75] Bashe, et al., *IBM's Early Computers*, 232-237.
[76] Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, New Jersey: Princeton University Press, 1972), 310.
[77] William Aspray, *John von Neumann and the Origins of Modern Computing* (Cambridge, Massachusetts: MIT Press, 1990), 80-81.
[78] Jan Rajchman, "Early Research on Computers at RCA," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 468.
[79] Bashe, et al., *IBM's Early Computers*, 232 and 271-272.
[80] For example, IBM finished the NORC a couple of years after completion of Whirlwind but with its own money and a different design. The NORC operated much faster than Whirlwind. Flamm,

More fundamental technologies originated in the ABC, a computer costing one-thousandth as much. That shows extraordinary things can be accomplished with little money. Indeed, a lesson of the ABC might be that scarcity spurs creativity. Moreover, considering the fate of the Arithmetical Machine, Whirlwind suggests a variation of Gresham's Law: the federal government can choke out privately funded research. Worst of all, Whirlwind demonstrated that government funding tends to go to those with political advantage, not to uses with citizens' interests at heart. Historians assume government poured so much money into computers, that it must have been proportionally responsible for their success. Money spent is not necessarily money wisely spent, however.[81] Words Adam Smith wrote in the eighteenth century retain potent implications today:

> The natural effort of every individual to better his own condition, when suffered to exert itself with freedom and security, is so powerful a principle, that it is alone, and without any assistance, not only capable of carrying on the society to wealth and prosperity, but of surmounting a hundred impertinent obstructions with which the folly of human laws too often incumbers its operations; though the effect of these obstructions is always more or less either to encroach upon its freedom, or to diminish its security.[82]

Coincident with the electronic digital computer has been the great rise of the federal government as a major source of funding for research. A relationship between governments and computers began much earlier than World War II, however. The very concept of the digital computer—and simultaneously government spending huge amounts on it—originated in England in the early nineteenth century with Charles Babbage. Calculating devices existed before, but none

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Creating the Computer, 9. The information is contained in "Table 2-1. Progress in Machine Computation Speeds."

[81] As told by historian David F. Noble, the development of computer-controlled machine tools has striking parallels to Whirlwind. Soon after World War II, American manufacturer John T. Parsons hit upon an idea to use EAM equipment to guide machine tools to make helicopter blades with greater precision than possible with conventional manual control, which was actually unsuitable. Parsons approached IBM and found the company enthusiastic, and it agreed to jointly develop the concept. However, Parsons also went to the Air Force to finance part of the project. To his lasting regret, he then asked MIT for technical advice. By hook and by crook, MIT and the Air Force took over, eventually eliminating both IBM and Parsons from the effort and reformulating the concept to their own ends. The result was numerical controlled machine tools so complex and expensive that only machine shops receiving government subsidies could afford them. Eventually, machine tools based on Parson's simpler idea did find common use. Involvement by MIT and the government set back numerical controlled machine tools by years and wasted tremendous amounts of money. See, Noble in *Forces of Production: A Social History of Industrial Automation* (New York City: Alfred A. Knopf, 1984), 79-143 and 195-239.

[82] Adam Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, 5th ed. (New York: Modern Library, 1985), 261.

nearly so advanced. Babbage conceived of calculators that approached, and one that perhaps met, all requirements for a true computer, albeit mechanical.

How Babbage got his ideas is not clear, although a project directed by engineer Gaspard Riche de Prony in France to construct trigonometric and logarithmic tables provided an inspiration. While organizing the effort, involving so many calculations it might otherwise have been impossible to accomplish, de Prony happened to read the first of *Wealth of Nations*, and it struck him to "manufacture logarithms" as Smith described the manufacture of pins using division of labor.[83] His employees thus came in three groups. One consisted of five or six mathematicians who determined formulae and supervised. Seven or eight calculators made worksheets for some sixty to eighty assistants to complete.[84] Interestingly, the latter group comprised mostly ex-hairdressers no longer employable in their original occupation because of the French Revolution and changing styles.[85]

The assistants did not understand mathematics but no matter. De Prony arranged the effort around the numerical technique of finite differences. Mathematics is full of delightful hidden patterns that emerge miraculously for those privy to its secrets, and the method of differences takes advantage of one. It happens that if a polynomial is solved for enough successive values, and if the differences of the answers are calculated, and the differences of those, and so on for enough differences, eventually the differences become a constant. A consistent pattern has at that point revealed itself in full. As many values as are wanted can be found by repetitively tracking through the steps in the pattern and making similar successive calculations, either additions or subtractions depending on the method used. Each sequence of calculations becomes the basis for the next iteration, beginning each time with the constant and ending with a new value.

It was a laborious process but worked for creating tables. The assistants used arithmetic to complete the worksheets, which they gave back to the calculators for checking. Mathematicians had the critical task of selecting formulae. The precise one might not be a polynomial, as with logarithmic or trigonometric functions. The mathematicians then had to find a polynomial that approximated the function and could be substituted over at least part of the argument.[86]

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[83] I. Grattan-Guinness, "Work for the Hairdressers: The Production of de Prony's Logarithmic and Trigonometric Tables," *Annals of the History of Computing* 12, no. 3 (1990), 178-179.
[84] Charles Babbage, "A Letter to Sir Humphry Davy, . . . on the Application of Machinery to the Purpose of Calculating and Printing Mathematical Tables," 1822; reprint in Martin Campbell-Kelly, ed., *The Works of Charles Babbage* (London: Pickering and Chatto, 1989), Vol. 2, 11-12.
[85] Grattan-Guinness, "Work for the Hairdressers," 179.
[86] Paul Ceruzzi, *The Reckoners: The Prehistory of the Digital Computer, From Relays to the Stored Program Concept* (Westport, Connecticut: Greenwood Press, 1983), 63-64.

Babbage was enough of a mathematician that he won the prestigious Lucasian Professorship at Cambridge in 1828. Isaac Newton once held that same chair.[87] It carried a stipend of eighty to ninety pounds sterling per year,[88] but Babbage did not so much as deliver a lecture for his pay.[89] He continued doing instead what he had always done: pursue numerous personal interests and travel extensively. On a trip to France, probably in 1819, he learned of de Prony's project, which impressed him immensely both for its methods and because the French Government paid for it.[90] A few months later Babbage helped his friend John Herschel, son of eminent astronomer William Herschel, construct astronomical tables. Babbage and Herschel made decisions and left routine calculations to be "distributed amongst several computers," something like de Prony. Babbage nonetheless found the work tedious and unavoidably full of errors, and it occurred to him that table making could be mechanized.[91] After due reflection, he built what he called a Difference Engine that could calculate two orders of differences. He wrote the President of the Royal Society of London, Humphry Davy, in 1822 to solicit money from the British Government for construction of a full-scale version.[92] The possibility of having error-free navigation tables enticed the government to agree.[93]

The Difference Engine was intended to substitute for the bottom echelon of de Prony's mental laborers, the assistants. Its design allowed solutions to six orders of differences and answers to sixteen decimal places. A mathematician still had to set up the problem into repetitive steps. The machine could then emulate the algorithm, solving consecutive new values by addition, without error, as long as someone turned its crank handle. To further eliminate errors, the engine was to automatically print values in tables. The Difference Engine must surely rank among the great inventive ideas of all time.

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87 The Lucasian Professorship of Mathematics had been privately endowed by Henry Lucas in 1640. Kealey, *The Economic Laws of Scientific Research*, 79.

88 Charles Babbage, *Passages from the Life of a Philosopher*, ed. Martin Campbell-Kelly (New Brunswick, New Jersey: Rutgers University Press, 1994), 24.

89 Martin Campbell-Kelly, Introduction to *Passages from the Life of a Philosopher* by Charles Babbage, ed. Martin Campbell-Kelly (New Brunswick, New Jersey: Rutgers University Press, 1994), 18.

90 Babbage, "A Letter to Sir Humphry Davy," 10.

91 Charles Babbage, "The Science of Number Reduced to Mechanism," 1822; reprint in Martin Campbell-Kelly, ed., *The Works of Charles Babbage* (London: Pickering and Chatto, 1989), Vol. 2, 15.

92 Babbage, "A Letter to Sir Humphry Davy," 6-14.

93 Starting 1766, the British Government paid for the yearly production of the *Nautical Almanac*, sets of hand-calculated nautical tables. Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York City: BasicBooks, 1996), 10.

The architecture of the Difference Engine involved calculation with digits in parallel but number sets sequentially. Calculating mechanisms consisted of linked trains of gears that also stored numbers. Such dual-purpose elements are called accumulators, although Babbage did not use that terminology. A different accumulator activated to process each step of the algorithm. Rather than have accumulators sit idle, Babbage had upstream ones began the sequence of calculations leading to the next value even as downstream accumulators finished the current value. This parallel-computing technique is now called pipelining, and a somewhat similar method is common today.[94] The Difference Engine was to measure eight feet high, seven feet long, and three feet wide and contain some 25,000 pieces, but it was never finished. Babbage manufactured less than one-half the total parts, assembled a demonstration model with 2,000 of them, and the rest were eventually scrapped. He spent a substantial fortune, partly his own, but also 17,470 pounds sterling of public money.[95]

Among the reasons Babbage did not complete the Difference Engine was that he did not get along with his chief engineer, Joseph Clement. A final break between the two men occurred in 1833 in a dispute over expenses and relocating to a new shop. Clement refused to do any more on the project and retained all drawings and machine tools, as permitted legally. That effectively put an end to the Difference Engine.[96] Babbage always had a number of endeavors underway simultaneously, another reason he did not finish the Difference Engine, and coincident with work on it published *Reflections on the Decline of Science and Some of its Causes* in 1830. He wrote the book to excoriate the Royal Society, of which he was a member, for reasons unnecessary to discuss here. The book also sought greater support of science by government. Babbage then helped found the British Association for the Advancement of Science to provide an alternative to the Royal Society for

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[94] Allan G. Bromley, "The Evolution of Babbage's Calculating Engines," *Annals of the History of Computing* 9, no. 2 (1987), 115-117. Babbage claimed the Difference Engine could calculate with numbers to twenty decimal places. Babbage, *Passages from the Life of a Philosopher*, 34.

[95] Doron D. Swade, "Redeeming Charles Babbage's Mechanical Computer," *Scientific American* 268, no. 2 (February 1993), 87-88.

[96] It has been thought that machine tools of the early nineteenth century lacked the precision needed to build a difference engine. Historian Doron Swade found otherwise. Measuring parts from the original Difference Engine, Swade discovered that Clement routinely achieved tolerances of 1.5 to 2.0 thousandths of an inch. Using the same tolerances, Swade fabricated a working replica of the Difference Engine No. 2, a later version. See, Swade, "Redeeming Charles Babbage's Mechanical Computer," 90-91.

representing science to government. The Association became more controversial than effective, and true to his famously irascible nature, Babbage had a falling out with that organization as well.[97]

Babbage had a decidedly modern viewpoint on science and government funding its pursuit. As Babbage saw things, the chief strength of Britain lay in manufacturing. Manufacturing expertise derived from applied sciences, which found its sources in "abstract Science." Moreover, following Adam Smith, division of labor could be as productively applied to exertions mental as those physical. It therefore followed that manufacturing could benefit from further specialization of mental labors and increased emphasis on theoretical studies. As Babbage put it: "Discovery of the great principles of nature demands a mind almost exclusively devoted to such investigations; and these, in the present state of science, frequently require costly apparatus, and exact an expense of time quite incompatible with professional avocations." Thus, sounding like Bush, he proposed that it might be, "politic in the state to compensate for some of these privations, to which the cultivators of the higher departments of science are exposed."[98] He believed government backing of science gave Britain its best hope of improving its manufacturing capabilities and economic situation.[99]

Modern ideas or not, Babbage had questionable justification for promoting government funding of science. Government gave him a huge sum of money, but he did fulfill his part of the bargain. More to the point, Britain did quite well without the funding. Most tellingly, Europe experienced a population boom during the eighteenth and nineteenth centuries. Historical precedent suggested that people should have starved with the next inevitable crop failure. People did starve, in fact, but no longer in Britain. It had bad harvests, certainly, but the British thrived, confounding expectations. From 1780 to 1860 the population of Great Britain almost tripled but *per capita* income rose from eleven to twenty-eight pounds sterling, a major increase even with cost of living changes. Costs of many items went down. For instance, cloth that cost seventy or eighty shillings in 1780 went for five shillings in 1850.[100] Britain did so well because of productivity improvements associated with the Industrial Revolution, thanks in good part to new textile machinery, steam

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[97] Anthony Hyman, *Charles Babbage: Pioneer of the Computer* (New York: Oxford University Press, 1982), 88-93, 130-133, and 149-156.

[98] Charles Babbage, *On the Economy of Machinery and Manufactures*, 4th ed. (1835; reprint New York: Augustus M. Kelly, 1971), 379-380.

[99] The linear model of innovation can be traced back at least to Francis Bacon (1561-1626), more lawyer than scientist, but who advocated organized scientific research funded by the state.

[100] D. N. McCloskey, "The Industrial Revolution 1780-1860: A Survey," in Roderick Floud and Donald McCloskey, eds., *The Economic History of Britain since 1700*, (Cambridge, England: Cambridge University Press, 1981), Vol. 1, 103-110. Charles Babbage gave numerous examples of common items that experienced dramatic price decreases during approximately the period 1800 to 1830. Babbage, *On the Economy of Machinery and Manufactures*, 153-159.

engines, iron making processes, and the like, all in consequence of investment of private capital. The exception was Ireland, which remained primarily agrarian and suffered brutal famine.

Deprivation occurred in Great Britain and the negative side of capitalism must shoulder some blame. In particular, building industry required investment of savings, and much of the sacrifice was initially borne by laborers in the form of lower wages. However, the unsavory reputation of the Industrial Revolution has less to do with deterioration of quality of life—living standards improved as never before—than the fact that capitalism rose together with modern democracy, both stemming from popular demand for more freedoms and equality. Economic historian Robert L. Heilbroner has noted that the forces of democracy subjected capitalism to scathing criticism and reforming influences from the beginning and with little regard to actual amelioration in conditions.[101]

Furthermore, as far as social misery existed during the Industrial Revolution, responsibility must largely be attributed to natural causes, such as poor harvests, or to actions by government. Antiquated monetary policies and frequent wars caused hardships, for example. Bad laws did too. Poor Law encouraged people to stay put in poverty instead of relocating to find readily available work. Corn Laws meant people unnecessarily went hungry during lean years by restricting importation of grains.[102] Corn Laws curiously also gave impetus for the rise of railroads. It became more cost effective to move goods with steam engines than with horses, a million of which had provided locomotive power in England, and each consumed on average enough grain to feed eight people.[103] Adam Smith's famous "invisible hand," paraphrased here as the collective genius of individuals, looks after nations better than their governments do.

As for the wars in which the British Government involved the nation and their impact on innovation, historian T. S. Ashton noted the same, if underreported, phenomenon evident from World War II, as follows:

> Those who take the perverse view that war is a spring of technological progress may be reminded that each of the major peaks (in numbers of British patents filed)—1766, 1769, 1783, 1792, 1802, and 1824-5—came in a time of peace. And those who believe that the wind bloweth where it listeth may well ponder the fact that at each of these dates the rate of interest was below the prevailing level, and that at each of them expectations of profit were running high.[104]

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[101] Robert L. Heilbroner, *The Making of Economic Society* (Englewood Cliffs, New Jersey: Prentice-Hall, 1962), 81-88 and 97.
[102] T. S. Ashton, *The Industrial Revolution: 1760-1830* (New York: Oxford University Press, 1969), 76-81 and 108-111.
[103] Wolfgang Schivelbusch, *The Railway Journey: The Industrialization of Time and Space in the 19th Century* (Berkeley, California: University of California Press, 1986), 4-5. Schivelbusch attributed Adam Smith for information on the ratio of food consumed by horses to that by people.
[104] Ashton, *The Industrial Revolution*, 63.

Government played only an indirect role in the prosperity of nineteenth-century Great Britain, and the influence of science was equally ambiguous, although usually cited as a major factor. For instance, according to Ashton: "Physicists and chemists, such as Franklin, Black, Priestley, Dalton, and Davy, were in intimate contact with the leading figures in British industry: there was much coming and going between the laboratory and the workshop, and men like James Watt, Josiah Wedgwood, William Reynolds, and James Keir were at home in the one as much as in the other." It is worth noting that Keir was a physician but Watt and Wedgewood had little formal education. Most inventors created more by cleverness and hard work than application of science, in fact. Among the more famous innovators of the Industrial Revolution, and in parenthesis their backgrounds, were Thomas Newcomen (ironmonger), John Kay (clockmaker), James Hargreaves (weaver), Richard Arkwright (barber), Peter Stubs (innkeeper), Benjamin Huntsman (clockmaker), Samuel Crompton (weaver), Henry Maudslay (mechanic), George Stephenson (engine-wright), John Wilkinson (ironmaster), Abraham Darby (ironmaster), and Henry Cort (navy agent).[105] The ingenious men responsible for the technology of the Industrial Revolution were overwhelmingly of the most common sort, with humble births and modest educations.[106]

Indeed, Babbage had an arguably valid point about the poor quality of science in Britain. Many thought British science in decline since Newton. Insistence on the archaic notation of Newtonian calculus as opposed to the more powerful and independently developed notation of Gottfried W. Leibniz used elsewhere in Europe epitomized the situation. Babbage bridled at the failure to adopt Leibnizian calculus even as a student. Never one to refrain from exerting his opinion, he and Herschel published an essay, "The Principles of pure D-ism in opposition to the Dot-age of the University," advocating the change.[107] The title is an epigram that got to the essence of the notational differences and simultaneously tweaked the sensibilities of his professors at Cambridge. Some of *Reflections on the Decline of Science* reflected that same spirit.

Even if not as sophisticated for a time as some of that on the Continent, and though it had minimal influence on the Industrial Revolution to 1860, or so, British science did have remarkable achievements. In 1831, for example, a year after Babbage published his polemic warning of neglect

[105] Ashton, *The Industrial Revolution*, 12-14. Keir made his name in chemicals; Wedgwood in crockery; Watt, Newcomen, and Stephenson in steam engines or locomotives; Reynolds, Stubs, Huntsman, Wilkinson, Maudslay, Darby, and Cort in iron, steel, or metalworking; and Kay, Hargreaves, Arkwright, and Crompton in textile machinery.
[106] Heilbroner, *The Making of Economic Society*, 77-81.
[107] Babbage, *Passages from the Life of a Philosopher*, 21.

of science, Faraday discovered electromagnetic induction. He moved a coil of wire in a magnetic field and produced an electrical current. Faraday's discovery is an example of how scientific discoveries increasingly became important for practical applications, as Babbage anticipated. Even so, British science continued to be mostly privately funded into the twentieth century.

France also had distinguished scientists doing first-class work, but unlike in Great Britain, the French Government backed science generously. De Prony's project was typical. Oddly, despite massive public spending on science, and despite its high quality, France remained relatively poor. It lagged Britain by fifty years going into an industrial revolution. All this suggests that, its science notwithstanding, France suffered because of *dirigisme*, its system of centralized economic control and onerous taxes. Britain did better because it enjoyed a freer market and light taxes.[108] In France, "trade is in disgrace," while in England, "it is highly respected," reported the no-nonsense Adam Smith, giving a characteristically trenchant explanation.[109] It is instructive that the French gained no more from the computing project of de Prony than the British did from that of Babbage. De Prony finished the mathematics tables, nineteen volumes at end of 1801, but financial troubles forced France to cancel plans to print them.[110]

No doubt Babbage advocated government funding for science because he believed it best for his nation, as Bush did for his, and as other people have for theirs. Adam Smith, of a different mind, commented sagely, if cynically, that he had, "never known much good done by those who affected to trade for the public good." That person, he said, "who should attempt to direct private people in what manner they ought to employ their capitals, would not only load himself with a most unnecessary attention, but assume an authority which could safely be trusted, not only to no single person, but to no council or senate whatever, and which would nowhere be so dangerous as in the hands of a man who had folly and presumption enough to fancy himself fit to exercise it."[111] Little wonder that, with the ascendancy of progressive thinking in the twentieth century, Smith fell out of favor.

With the failure of the Difference Engine, the British Government temporarily learned its lesson, and Babbage got no more money. Babbage doggedly turned his prodigious talents to a more advanced machine. Useful though a calculator that solved problems by the method of finite differences could have been, it had limitations. It occurred to him to create a more flexible calculator

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[108] Kealey, *The Economic Laws of Scientific Research*, 60-89.
[109] Smith, *Wealth of Nations*, 92-93.
[110] Grattan-Guinness, "Work for the Hairdressers," 180-181.
[111] Smith, *Wealth of Nations*, 225-226.

by linking the accumulators to allow modification of the constant by feedback of the last calculated value. He phrased the concept as the "engine eating its own tail."[112] He thought such a machine must be forbiddingly complex, but then realized it could be simplified by separating the mechanism that stored numbers from the one that performed computations. On that basis, Babbage began design of the Analytical Engine. Taking terminology from textile mills, he called the computational and storage parts of the engine the mill and store, respectively (and suggesting that comparisons to the brain were not inevitable, after all).[113] The Difference Engine did only addition, but the Analytical Engine could also subtract, multiply, divide, and find roots.

It might seem that a machine that does only arithmetic can hardly be considered a computer, but remember, that and conditional logic are about all any digital computer does mathematically. The Analytic Engine was to be more powerful than the Difference Engine, not so much by performing more arithmetic operations, but because it could solve disparate algorithms. Babbage considered alternative programming methods and, like Hollerith, adopted punched card technology from the Jacquard loom to enter mathematical formulae and data. Babbage declared his Analytical Engine a "finite machine" that could do "calculations of unlimited extent."[114] A friend, Ada Augusta, Countess of Lovelace and only legitimate daughter of Lord Byron, described the Analytical Engine more eloquently as befitted her heritage. She averred poetically, "We may say most aptly that the Analytical Engine weaves algebraical patterns just as the Jacquard loom weaves flowers and leaves."[115]

No complete description of the Analytical Engine exists unfortunately, at least in part because Babbage, a perfectionist, kept modifying its design. He worked on it sporadically for the rest of his life but built little or none of it. He also designed a more efficient difference engine, referred to as Difference Engine No. 2, to entice the British Government to supply more funding so he might fulfill his original bargain. The government would have none of it. After Babbage died in 1871, just shy of his eightieth birthday, his son Henry succeeded in building some of the Analytical Engine. He also inherited his father's obsession of begging money from government. The British Association for the Advancement of Science reviewed his request but denied it. The review committee was obviously impressed with the Analytical Engine and thought it could be useful. However, it worried

[112] Bromley, "The Evolution of Babbage's Calculating Engines," 120.
[113] Campbell-Kelly, Introduction to *Passages from the Life of a Philosopher*, 23.
[114] Charles Babbage quoted in Brian Randell, *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 13.
[115] Ada Augusta quoted in Campbell-Kelly, Introduction to *Passages from the Life of a Philosopher*, 27.

the engine might take "tens of thousands of pounds at least" to construct. Moreover, since Babbage had never finished the design, there was some chance that it could not be made to work. The committee closed by recommending consideration instead of a special-purpose engine for solving simultaneous algebraic equations.[116] It is on that note that Atanasoff and Berry undertook their initiative in digital computers approximately sixty years later.

If Babbage failed to complete an engine, he did leave posterity the idea of the digital computer. Some historians of computers believe that among his numerous insights may even have been that of the stored-program concept.[117] However, no one argues that the stored-program concept in the twentieth century came from Babbage, and it is difficult to gauge his overall impact. Eckert and Mauchly claimed not to know of him at the time that they built the ENIAC, for example.[118] Other pioneers had at least an awareness of Babbage. References to him and his engines were common in the 1930s, so anyone doing even cursory study of computational devices should have encountered them.[119] An article in 1936 by Bush referred to Babbage's work, for example.[120] The next year, Aiken mentioned Babbage in his proposal for the ASCC.[121] Atanasoff knew of him but apparently by reading encyclopedia articles so general as not to be of much practical value.[122]

Whatever it owed to Babbage, the next major attempt to build a digital computer by the British succeeded admirably. They devised electronic digital computers called Colossi to do cryptanalysis during World War II. One person who had some influence on the Colossi was the mathematical genius Alan Turing. Turing admired Babbage, although evidence for this comes later,

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[116] "Report of the Committee . . . of constructing Mr. Babbage's Analytical Machine, and of printing tables by its means," 1879; reprint in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 63-65.
[117] Randell, *The Origins of Digital Computers*, 375-376.
[118] J. Presper Eckert, "The ENIAC," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 527.
[119] N. Metropolis and J. Worlton, "A Trilogy on Errors in the History of Computing," in *First USA-Japan Computer Conference Proceedings: October 3-5, 1972, Tokyo, Japan* (Montvale, New Jersey: American Federation of Information Processing Societies, 1975), 683-685. See, in particular, "Table I. Selected Chronological References to Babbage," 685.
[120] See Vannevar Bush, "Instrumental Analysis," *Bulletin of the American Mathematical Society* 42 (1936).
[121] Howard Aiken, "Proposed Automatic Calculating Machine," 1937; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 195-196.
[122] See, for example, "Charles Babbage" and "Calculation Machines" in *Encyclopaedia Britannica*, 13th ed., 1926; J. V. Atanasoff, New Market, Maryland, interview with B. Kaplan, 23 August 1972, 6-8. Smithsonian.

after Colossi and the war, while Turing designed a computer named ACE.[123] ACE stands for Automatic Computing Engine, a name deliberately reminiscent of the engines of Babbage. However, copies of *First Draft* had been distributed by the time Turing began ACE, and he cited von Neumann and not Babbage in his proposal.[124] In any case, Turing's legacy is largely derived from a 1937 publication that established theoretical underpinnings for the capabilities and, perhaps, limitations of computers, and there was not a clear connection to Babbage in it. The reason is that the paper, "On Computable Numbers, with an Application to the *Entscheidungsproblem*," paradoxically did not explicitly propose a physical machine. Turing imagined instead an idealized device as a means to solve a problem posed by German mathematician David Hilbert. It happened that Turing's abstraction bore remarkable resemblance in concept to the modern digital computer, although there is evidence that Turing may have thought at the time about eventually building one.[125]

Hilbert wanted to establish a solid foundation for mathematics, and as part of that program proposed the *Entscheidungsproblem*, or decision problem, in which he asked if there existed a general procedure that in theory could solve all problems in mathematics. Turing attacked the question by first attempting to model how a machine might reason like a human being. The theoretical "computing machine" he conceived had a finite number of internal states and limitless external storage, imagined as an infinitely long paper tape arranged in discrete blocks. The machine dealt with one block at a time. It could read a block; it could make a mark; and it could erase a mark already there. It could also move the tape right or left, but still only one block at a time.[126] Given a problem, the machine labored on automatically, assiduously making decisions from information on tape and in memory, until coming to a stop, the answer appearing as a sequence of marks on the tape to one side.

Simplistic as this may seem, Turing's imaginary mind machine was quite powerful, if plodding. Turing recognized that such a device could manipulate detailed instructions and numbers alike as binary coding. Indeed, a Turing machine, as these idealized computers were called, could be created to run any algorithm. Furthermore, a universal Turing machine could encompass the capabilities of all Turing machines. Even so, Turing found the *Entscheidungsproblem* had no

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[123] Metropolis and Worlton, "A Trilogy on Errors in the History of Computing," 686.
[124] Randell, *The Origins of Digital Computers*, 376.
[125] Martin Davis, "Mathematical Logic and the Origins of Modern Computers," in *Studies in the History of Mathematics*, ed. Esther R. Phillips, *Studies in Mathematics* (Mathematical Association of America, 1987), Vol. 26, 151-152.
[126] A. M. Turing, "On Computable Numbers, with an Application to the *Entscheidungsproblem*," *Proceedings of the London Mathematical Society*, Second Series 42 (1937), 231.

solution. There was no general algorithm guaranteed to solve all conceivable problems. No matter the algorithm chosen, there was a chance that a particular problem might run forever, the machine unable to stop.[127] We might alternatively say that no program exists guaranteed to solve all problems without the computer crashing or becoming caught in an endless loop.

A universal Turing machine manifested physically could be like the EDVAC, or any general-purpose digital computer for that matter. Conversely, modern computers are said to be universal Turing machines, since Turing implied the stored-program concept. Furthermore, a key characteristic of a Turing machine was its ability to make decisions, known as conditional branching. That capability is sometimes said to separate a computer from a calculator.[128] Despite the power of his ideas, Turing has not been credited much for modern computers.[129] His paper remained largely unknown until after the war.

Turing did influence computer development, nonetheless, and probably more than historians realize. One influence was through von Neumann, who met him in 1935 at Cambridge, England, where Turing was an undergraduate and von Neumann lectured as visiting professor.[130] The men had similar mathematical tastes (in fact, von Neumann had used a Rockefeller Foundation grant for postdoctoral study under Hilbert), and Turing had submitted for publication an improvement to something von Neumann had done. The next year, Turing went to Princeton to study under mathematician Alonzo Church, who had derived a negative answer to the *Entscheidungsproblem* using a different method of "effective calculability."[131] Von Neumann also had residence at Princeton at the IAS.[132] In his dissertation at Princeton, Turing defined the O-machine, a universal Turing machine outfitted with an "oracle" that allowed it to solve problems otherwise not computable. Fantastic though that sounds, computer scientists in the field of hypercomputation are attempting to create something similar, although they have yet to catch up with Turing.[133] Von Neumann recommended Turing for a prestigious fellowship, which he received,[134] and then offered to make him his assistant. Turing declined to return to England. Von Neumann later made "On

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[127] Roger Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics* (New York: Oxford University Press, 1989), 34-64.
[128] Patterson and Hennessy, *Computer Organization and Design*, 111.
[129] Randell, *The Origins of Digital Computers*, 376.
[130] Davis, "Mathematical Logic and the Origins of Modern Computers," 150-151.
[131] Turing, "On Computable Numbers," 231.
[132] Aspray, *John von Neumann and the Origins of Modern Computing*, 176-177.
[133] B. Jack Copeland and Diane Proudfoot, "Alan Turing's Forgotten Ideas in Computer Science," *Scientific American* 280, no. 4 (April 1999), 101-103.
[134] Davis, "Mathematical Logic and the Origins of Modern Computers," 150-151.

Computable Numbers" mandatory study for designers of the IAS computer. His famous work in automata also derived in part from Turing. Moreover, von Neumann wrote *First Draft* around the logical calculus of McCulloch and Pitts, who later cited Turing as important to their understanding.[135] Given his and Turing's association and interest in the brain, there seems no reason to attribute any of von Neumann's theoretical thinking on computers to Eckert and Mauchly.

Back in England, Turing became part of a secret effort to break German military codes. His exact contributions are unknown, but he first helped improve cryptanalytic machines called Bombes.[136] He also assisted with design of a series of decoding devices called Heath Robinsons, each of which used electronic circuits to compare input from two paper tapes scanned at high speeds by photoelectric readers. Coordinating the tapes proved difficult and after failing to make tracking mechanisms reliable, a team member, Tommy Flowers, suggested Colossus.[137] It was a digital computer with about 1,500 vacuum and gas tubes, and including electronic binary counting and logic circuits. Plugboards permitted programming, much like the ENIAC. It had a high-speed input similar to a Heath Robinson but needed only one tape, because a small internal memory allowed derivation of data that the second tape supplied in the earlier machines. Colossus was completed in December 1943, eleven months after start of the project and two years before the ENIAC.

Colossus was actually a prototype, and nine or ten MARK II Colossi followed. No two turned out exactly alike, but the MARK II Colossi needed about 2,400 tubes each and operated approximately five times faster than the original. More important, the Colossi proved reliable and, with the other cryptanalytic machines developed by the British, made significant contributions to defeating the Germans. Turing's paper, "On Computable Numbers," influenced the design of the Colossi, but he did not otherwise. Turing spent his time on related code-breaking projects. The Colossi did not qualify as universal Turing machines, that is, as general-purpose computers. Neither did the ENIAC, but it is famous while the Colossi are not because they were kept secret until the mid-1970s and still have not been fully revealed.[138]

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[135] Aspray, *John von Neumann and the Origins of Modern Computing*, 180-181 and 189-206. See also footnote on page 313.

[136] I. J. Good, "Pioneering Work on Computers at Bletchley," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 35-36.

[137] Brian Randell, "Colossus: Godfather of the Computer," in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 350-351.

[138] B. Randell, "Colossus," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 47-89.

Many who helped with the Colossi continued computer developments in Great Britain after the war. Turing began ACE at the National Physical Laboratory in England using the basic design of the EDVAC. He incorporated his own ideas to increase its speed, including a technique called optimal coding that allowed faster retrieval of data from storage. He left the project in 1947, after changing the design of ACE several times. A miniature version, Pilot ACE, with 800 vacuum tubes was finished in 1951 and proved to be a useful computer.[139] MOSAIC[140] then got built based on an early design of ACE. MOSAIC apparently served in air defense something like Whirlwind did in the U.S. ACE itself was not finished until 1957, by which time magnetic core memory had made its mercury delay tube memory obsolete. As noted, EDSAC was completed in 1949, before similar computers in the United States. The British Government supported a number of other projects, including Muse, also called Atlas, a supercomputer finished in 1962 and equal to any at the time.

Nor did the British lack for commercial efforts. The British firm Ferranti Limited installed a commercial computer, the Ferranti Mark I, before Remington Rand delivered its first UNIVAC and then delivered eight more by 1958. The company J. Lyons produced a version of the EDSAC, the Leo,[141] for business applications. Nevertheless, the British computer industry failed to take off despite government support and availability of experienced designers. Ten times the number of companies went into computer manufacturing in the United States in the 1950s than in Britain. Prime Minister Harold Wilson felt compelled in 1964 to implement a special program to support his nation's computer makers. Even so, the British computer industry all but disappeared.[142]

Great Britain and the United States were not the only countries developing computers around World War II. Especially intriguing were machines in Germany made by Konrad Zuse. In fact, Zuse claimed to be the original inventor of the computer.[143] His claim has merit, although his machines through 1945 were neither electronic nor true computers. Independent of work elsewhere, however, Zuse conceived of computers approximating von Neumann machines, including the stored-program concept. That he did not make greater progress was more due to circumstances than lack of vision.

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139 J. H. Wilkinson, "Turing's Work at the National Physical Laboratory and the Construction of Pilot ACE, DEUCE, and ACE," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 101-114.
140 MOSAIC was an acronym for Ministry of Supply Automatic Integrator and Calculator.
141 Leo was an acronym for Lyons Electronic Office.
142 Flamm, *Creating the Computer*, 138-142 and 148-150; Flamm, *Targeting the Computer*, 174.
143 Zuse, *The Computer—My Life*, IX.

A friend, Helmet Schreyer, introduced him to electronics, and Schreyer, if not Zuse, probably would have built an electronic computer using Zuse's basic design if not for the war.

Zuse became interested in computers for the same reason that many pioneers did: He grew tired of making tedious mathematical calculations by hand. Zuse graduated from the Technical University of Berlin-Charlottenburg in 1935 and took employment as a structural engineer for the Henschel Aircraft Company. Problems in structures were frequently cumbersome or impossible to solve, including algebraic equation sets containing thirty or more unknowns. Zuse resolved to find a better way.[144] He quit his job and set up a workshop in his parent's apartment in Berlin to build a computer, although he knew nothing about them. Zuse attributed his subsequent success to hard work, but it built on remarkable ingenuity.

Zuse also studied wisely. He did not know at first of Babbage, but learned of him from an American patent examiner who denied his 1937 application for a program control and arithmetic unit. The examiner cited Babbage against the application.[145] However, Zuse had by then acquired such a sophisticated understanding of computers that Babbage had little to teach him. More important was Leibniz, who Zuse credited but gave few details. Zuse fortunately had studied Latin,[146] so he could read what were then obscure but topical writings by Leibniz that a friend with library privileges borrowed for him.[147] Besides the calculus, Leibniz invented a highly successful machine that could add, subtract, multiply, and divide.[148] He also did early work in two related areas basic to modern computers. The first was the binary number system, which Leibniz termed the "diadic" system.[149] The calculator he invented used decimal numbers, but he discussed the possibility of building binary calculators that represented digits with moving balls.[150] To complement his consideration of binary numbers, at least from the perspective of today, he also helped initiate mathematical logic. In 1666, when twenty years old, Leibniz proposed to establish a universal system of reasoning in *De Arte*

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[144] Ceruzzi, *The Reckoners*, 11.
[145] German patent authorities turned down his application for the same devices for "insufficient disclosure."
[146] Zuse, *The Computer—My Life*, IX, 4, 7, 33-34, and 109.
[147] Walther Buttmann, quoted in Zuse, *The Computer—My Life*, 37.
[148] Randell, *The Origins of Digital Computers*, 2-3.
[149] Konrad Zuse, "Method for Automatic Execution of Calculations with the Aid of Computers," April 1936; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 167.
[150] Randell, *The Origins of Digital Computers*, 3.

Combinatoria. He failed in that ambitious goal despite a lifetime of off-and-on-again effort, but in the attempt posited elementary concepts in logical mathematics.[151]

Finally, upon advice of a former teacher, Zuse studied more contemporary mathematicians. These included Hilbert, who besides posing the *Entscheidungsproblem*, advanced understanding of mathematical logic, among other things.[152] On this solid theoretical foundation, Zuse made substantial innovations in computing.

Zuse built six computers by end of World War II. All used binary numbers and logical switching. Their architectures separated arithmetic from memory units and performed calculations in parallel by digits but sequentially by number sets.[153] Most of his computers used floating-point number representation. Most were program controlled, but none fully general purpose. Finally, Zuse recognized the potential of stored-programs and programming languages. In a diary entry from 1937, for example, he discussed development plans including a, "stored or working plan (program)" that can "result from the preceding operations" . . . "and in this way (can) be built from itself."[154] However, none of the computers built by mid-1945 had the capability of storing a program.[155]

Zuse created his first computer with support from friends and family. About "the size of (an) 8-place dining-room table,"[156] the Z1 was entirely mechanical. Its compact and dependable sixteen-word memory contained hundreds of relays made with steel pins and strips of sheet metal and glass.[157] Zuse had less luck devising an arithmetic unit, necessarily more complex than the memory. He actually needed two arithmetic units working in parallel, one to process each of the two parts of floating-point notation. Furthermore, the arithmetic unit for digits did double service converting numbers between decimal and binary.[158] Four-digit decimal numbers were entered with a keyboard and converted to either seven binary places for magnitude or sixteen for digits.[159] A mechanical

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[151] Morris Kline, *Mathematical Thought from Ancient to Modern Times* (New York: Oxford University Press, 1972), 1188.
[152] Zuse, *The Computer—My Life*, 46-47 and 83. The specific work by David Hilbert that Zuse studied was *Principles of Mathematical Logic*, written with W. Ackermann and published in Germany in 1928.
[153] Zuse, *The Computer—My Life*, 124.
[154] Konrad Zuse, diary entry, 20 June 1937. Quoted in Zuse, *The Computer—My Life*, 44.
[155] Zuse, *The Computer—My Life*, 50.
[156] Karl-Ernst Hoestermann, quoted in Zuse, *The Computer—My Life*, 66.
[157] Randell, *The Origins of Digital Computers*, 160.
[158] Konrad Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 1962; reprinted in Brian Randell, ed., *The Origins of Digital Computers: Selected Papers*, 3rd ed. (New York: Springer-Verlag, 1982), 178-182.
[159] Zuse, *The Computer—My Life*, 203-204.

display gave output.[160] Zuse completed the Z1 in 1938, but it functioned only well enough to convince him to keep trying.[161]

Zuse had to find additional money before finishing the Z1. A manufacturer of specialized calculators gave him enough to complete the Z1 and build a second computer. Actually, the only thing new about the Z2 was a small, fixed-point arithmetic unit that Zuse connected to the old memory from the Z1. Schreyer, an electrical engineer, wanted to make the Z2 electronic,[162] but Zuse deemed it too risky. He compromised by using electromechanical relays in the arithmetic unit, which took about two hundred.[163]

When fabrication of Z2 was well along, Zuse got drafted into the German Army. He served six months before being sent back to the Henschel Aircraft Company to help design flying bombs. His job became part time, so with colleagues he established a business, *Zuse Ingenieurburo und Apparatebau*, and continued construction of the Z2. He finished it in 1940, but the second-hand telephone relays he used were not suited for the application, and the Z2 worked only long enough to demonstrate to a representative of the German Aeronautics Research Institute (DVL). The man was sufficiently impressed that he arranged for money for Zuse to build another computer.[164]

Zuse finished the Z3 in December 1941. Some consider it the first operational digital computer in history. However, the Z3 was not a true computer and had little memory. In its primary purpose of solving simultaneous equations, the largest determinant it could handle was apparently a three by three, easily done by hand.[165] The logical design of the Z3 followed closely on the Z1, but the Z3 contained electromechanical relays throughout, including 600 for the arithmetic units, 1,400 for memory, and 600 for controls and miscellaneous purposes. The relays were second-hand and of varying specifications, which made orchestrating their operations difficult.[166] Input of instructions came from tape made from discarded celluloid motion picture film punched by hand. Data was entered with a keyboard and output indicated by lamp display. Like the Z1, the Z3 used floating-point notation. It had a memory of sixty-four words of twenty-two binary digits each.[167]

A rotating drum synchronized operations, much like the ABC. However, while the ABC operated at sixty pulses per second, the maximum clock rate of the Z3 was about five pulses per

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[160] Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 180.
[161] Ceruzzi, *The Reckoners*, 25-26.
[162] Zuse, *The Computer—My Life*, 38 and 41-44.
[163] Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 183.
[164] Zuse, *The Computer—My Life*, 56-62 and 65.
[165] Ceruzzi, *The Reckoners*, 29-38.
[166] Zuse, *The Computer—My Life*, 62-63 and 201.
[167] Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 183.

second. Furthermore, while the Z3 could be programmed for a variety of tasks, its small memory limited its usefulness. Its cost has been estimated at the equivalent of $6,000 to $7,000, comparable to the ABC.[168]

Shortly after finishing the Z3, Zuse was inducted back into the army and marched east to war. Luckily, he got another exemption to return to the Henschel Aircraft Company to develop special-purpose computers for calculating the aerodynamics of the wings and tails of flying bombs. The S1, completed in 1942, contained about 800 relays. Bomb measurements had to be entered manually. The next year, Zuse built the more advanced S2, which allowed readings to be taken at the bridge that cradled the bombs, converted into electrical signals, and fed in automatically.

Schreyer assisted Zuse and found time to explore vacuum tube technology. He paired vacuum tubes with gas-filled lamps (such as small neon lights) to create circuits that conducted electricity only upon reaching a threshold voltage, but that continued to conduct at lower voltages. The combination made a more reliable discrete device than a vacuum tube alone. Zuse compared the arrangement to a relay, in which the tube substituted for the coil and the lamp for contacts.[169] Based on his investigations, Schreyer earned a doctorate from the Technical University of Berlin-Charlottenburg with a dissertation entitled, "The Tube Relay and the Techniques of its Switching."[170] He proposed a computer using some 2,000 vacuum tubes and equal number of lamps,[171] and with an anticipated clock rate of 10,000 pulses per second. Military officials refused, believing the war would be won before Schreyer finished. As a consolation, he received a contract to build a small test unit with one hundred tubes.[172]

Schreyer's test device became operational, but it and most of Zuse's computers did not survive the intense bombing of Berlin by the Allies. The S2 may have survived and been captured by the Soviets.[173] The one computer saved was begun in 1942 and completed just at war's end. That computer, the Z4, was like the Z3, but with a longer word length (thirty-two bits) and a mechanical memory, to which Zuse returned because of its compactness. He had wanted a memory of 1,024 words but settled for 512.[174]

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[168] Ceruzzi, *The Reckoners*, 29-38.
[169] Zuse, *The Computer—My Life*, 40.
[170] Ceruzzi, *The Reckoners*, 26.
[171] Zuse, *The Computer—My Life*, 58.
[172] Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 182. Also, Zuse, *The Computer—My Life*, 78.
[173] Zuse, *The Computer—My Life*, 64-65, 69-73, and 107.
[174] Ceruzzi, *The Reckoners*, 39.

Deteriorating conditions caused Zuse to flee Berlin in the final weeks of the war. Original designations for his computers were the V1, V2, V3, and V4, respectively, where V stood for *Versuchmodell* (Experimental). Zuse changed the names to avoid confusion with the infamous V1 and V2 rockets, where V meant *Vergeltungswaffen* (Retaliatory weapon). In relocating the Z4, the confusion proved helpful. Authorities cut red tape to help evacuate what they thought was a new weapon. Zuse thus procured a truck and moved the Z4 and his wife (also brand new) to safety. They eventually landed in a small town in Bavaria, where Zuse stored the computer in a stable. There it stayed until 1949, when the Swiss Federal Institute of Technology contracted for its use in Zurich. It proved useful and reliable.

Zuse continued in computers despite tough postwar conditions. In 1946, he finished developing the programming language he first envisioned in 1937. He called it the *Plankalkul* (Plan calculus). Thomas Watson learned of the Z4 and purchased an options contract for Zuse's patents. Moreover, Zuse, like Atanasoff, hoped to work for IBM. However, he ceased negotiations when IBM showed little interest in further development of the Z4. He then established a company he named Zuse KG and contracted with Remington Rand to build a tabulating machine using mechanical relays. That was what Remington Rand wanted, curiously. Zuse utilized pipelining to increase its speed, much like Babbage envisioned. The machine did not find regular service, but heralded a profitable business for Zuse designing and building electromechanical EAM equipment for Remington Rand through 1957.[175]

Zuse also built commercial computers, both general-purpose scientific and special-purpose business machines. He delivered the Z5 to an optics company in 1952. It used relays but operated six times faster than the Z4 and could make conditional jumps, unlike Zuse's earlier computers.[176] He built other computers, but none was electronic because of stipulations in the terms of Germany's surrender. The prohibition was lifted in 1955, and the Z22 shipped in 1958.[177] It used vacuum tubes, had a magnetic core memory, and sold well. The Z22 transitioned into the Z23, a transistorized computer. Zuse KG employed around 1,000 people at its peak in the early 1960s, but by then had financial troubles. Among the reasons was the difficulty of keeping abreast of rapidly changing technologies and demands of customers. Zuse produced relatively small machines that fit the modest budgets of European organizations in the 1950s. The market changed as the economy of Europe improved. Customers increasingly wanted large mainframe computers, which Zuse complained often

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[175] Zuse, *The Computer—My Life*, 48, 91-93, 107, 114-116, and 118-123.
[176] Zuse, "The Outline of a Computer Development from Mechanics to Electronics," 187.
[177] Flamm, *Creating the Computer*, 160-161.

had more to do with prestige than need. Whatever the case, he sold his company in 1964 to Brown, Boveri and Company AG, which sold it in turn to Siemens.[178]

Siemens performed poorly as a computer manufacturer despite (or because of) the West German Government making it the nationally favored producer. Siemens survived by making IBM-compatible computers, which for its mainframes used Japanese designs. Another company, Nixdorf, started in 1968, became the most successful manufacturer of computers in Germany. Instead of relying on government guidance and handouts, it specialized in minicomputers as they became popular again and aggressively sought markets around the world.

A slowdown in technical progress in the last century might be attributable to some marginal invention factor, in which innovation came easily at first but progressively more difficult. Perhaps the emphasis on basic research as opposed to invention itself helps account for the decline. More generally, however, the experiences of the various nations suggest that public sponsorship has been central to decreasing rates of invention. Evidence is that the more governments tried to foster science and technology, the less innovation and economic growth resulted. Admittedly, the government of the United States invested lavishly in computer research, and its industry thrived. However, the British Government also spent heavily, but its industry fizzled, and not because of the inferiority of British research. Into the 1950s, Great Britain often equaled, or surpassed, America in computer-related innovation. The usual explanation for why the industry failed in Britain is that, burdened with rebuilding after the war, its government simply could not contribute as much toward research.[179]

How then to explain the disparity of outcomes including Japan and former Soviet Union? No nation identified itself more closely with science, esteemed scientists and engineers so highly, or spent a greater percentage of its GDP on research as the USSR. Even so, it had amazingly little to show for its investment and is not remembered for technologies other than weapons and spacecraft.[180] The Soviet Union did well building heavy industry, as long as it could derive technology from other countries. It stood about equal to the West through the 1950s in computer technology, and indeed, had a budding computer industry. A decade later, the USSR lagged the U.S. by about five years, total state control notwithstanding. Crucial as computers must be for managing a command economy, it unabashedly started copying IBM equipment, but to no avail: it kept falling further behind.[181] It looks

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[178] Zuse, *The Computer—My Life*, 135-142 and 153.
[179] Flamm, *Targeting the Computer*, 157-158; Flamm, *Creating the Computer*, 136 and 159-165.
[180] Kealey, *The Economic Laws of Scientific Research*, 193-194.
[181] Stanislav V. Klimenko, "Computer Science in Russia: A Personal View," *Annals of the History of Computing* 21, no 3 (July-September 1999), 24-25.

in retrospect that the only reason the USSR could compete in weapons and spacecraft is because those technologies were only slightly less government dominated in the U.S.

By contrast, Japan by the 1970s built a computer industry second only to the U.S. despite having been more devastated by war than Great Britain.[182] Moreover, the Japanese did not have the initial expertise of the British. Of course, the short answer of how the Japanese did it is that they worked hard and copied American technology, something like the Soviets. But a complete answer must admit that Japan, unlike the USSR and Britain, fostered a better environment for business.

Policy analysts used to credit Japan's economic success to its special form of capitalism, which mixed intense domestic competition with governmental guidance. It was believed that the high growth rate of the Japanese economy was primarily due to a policy of targeting key industries, such as computers, with extra funding. So impressive were the results that many strongly advocated adopting a similar policy in the U.S. With the severe downturn in the Japanese economy in the 1990s, however, economists took a second look at targeting and found its alleged benefits exaggerated. The chief Japanese government agency responsible for targeting in manufacturing has been the Ministry of International Trade and Industry (MITI). Rather than dispassionately picking industries with best growth potential, as had been supposed, MITI was rife with politics and gave something to everyone. To the extent that MITI favored industries, it tended to be those that then had low growth. As critics put it, MITI picked losers, not winners. Industries succeeded in spite of MITI.[183] MITI insisted that Honda stick with motorcycles, for example, and it had almost nothing to do with the rise of the consumer-electronics industry in Japan, a major success.[184]

An example of MITI targeting was the highly touted fifth-generation computer, a huge parallel computer with 1,000 processors begun in 1982. The supercomputer was to be so advanced that experts warned it might put Japan in a position to dominate the computer market worldwide. Some countries reacted by attempting to establish similar initiatives. For its part, the U.S. instigated several related collaborations with the Japanese. It all turned out much ado about nothing. MITI realized as early as 1985 that its design was flawed. It nevertheless continued to pour money into the computer until 1992, when the project was finally killed after having spent more than $400 million but achieving only a fraction of the original goals.[185]

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[182] Flamm, *Creating the Computer*, 172.
[183] Richard Beason and David E. Weinstein, "Growth, Economies of Scale, and Targeting in Japan (1955-1990)," Harvard Institute of Economic Research, Discussion Paper 1644 (10 June 1994), 1-9.
[184] Yergin and Stanislaw, *The Commanding Heights*, 162-164.
[185] David Swinbanks and Christopher Anderson, "Japan Stubs its Toes on Fifth-Generation Computer," *Nature* 356, no. 6367 (26 March 1992), 273-274.

Government involvement in research looks to have been counterproductive in Japan, like other places it has been tried. Fortunately for Japan, and contrary to popular belief, science there has been predominantly privately supported. The failures of MITI and low expenditures in government-financed research suggest that the Japanese computer industry built itself on its own.[186] The U.S. succeeded spectacularly in computers because it already had a vibrant office appliance industry, in particular, an IBM. In fact, the Japanese computer industry only became viable after the companies Fujitsu and Hitachi began producing IBM-compatible machines, aided by Gene M. Amdahl, a former designer for IBM.[187] More generally, that Japan and America have computer industries, while Great Britain, Germany, and Russia do not, probably has more to do with greater competitive spirit, lower public expenditure ratios (general government outlay as a percentage of nominal GDP), and commensurately moderate tax rates of the former.

As examples, in 1970 the public expenditure ratios of the U.S., Japan, and Great Britain were 30.0, 19.0, and 36.7, respectively. In 1996, the figures were 32.7, 36.2, and 41.8, respectively.[188] The great increase in Japan's public expenditure ratio may help explain its current economic malaise. As for taxes, Great Britain took the lead in the West after World War II in nationalization of industry and construction of a welfare state.[189] Its tax rate has averaged 40 to 50 percent of GNP. Taxes have been lower in Japan and the U.S., generally no more than 35 percent of GNP.[190]

Bush created a fable to justify sponsorship of science by the federal government, but he did so in the progressive spirit. Government had been slowly but inexorably expanding from the nation's beginning, but a fundamental shift in expectations of Americans began with the Great Depression. Those years of misery and deprivation have blithely been blamed on a failure of capitalism. The U.S. moved out of the Depression, it is asserted, when the federal government belatedly took responsibility for society through the myriad programs of the New Deal. Americans thus came to depend upon government to keep the economy moving, and its programs for science constituted a handful of many new spending initiatives.

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[186] Beason and Weinstein, "Growth, Economies of Scale, and Targeting in Japan (1955-1990)," 4.
[187] Flamm, *Creating the Computer*, 194-195.
[188] Henderson, *The Changing Fortunes of Economic Liberalism*, 52. Figures are from, "Table 4: Public Expenditure Ratios, 1970-96, for Core OECD Countries, Selected Years."
[189] Yergin and Stanislaw, *The Commanding Heights*, 22-27.
[190] Kealey, *The Economic Laws of Scientific Research*, 86 and 112. See also, "Figure 10.1. Business: Government Funding (part I)," 241.

The Depression involved a mix of factors not fully understood, but the truth is less flattering to government. Business cycles and financial miscalculations are intrinsic to capitalism, but government was itself implicated as the leading cause of the economic disaster. Federal government did not support science to any large extent before the Depression but exercised considerable influence over the economy, although nineteenth-century policies stressed free trade, the gold standard, and balanced budgets. Classical policies enforced discipline but gave little thought to dealing with the depressions that occurred regularly.[191] The next century brought progressive strategies, as exemplified by the creation of the Federal Reserve System in 1913. Wrong-headed monetary and fiscal policies transformed what should have been a relatively mild, nineteenth-century kind of depression into the Great Depression. *The Economist* magazine summarized the matter thusly: "Capitalism will always have dramas. It is governments that turn them into crises."

Charges that the Depression resulted from overproduction of manufactured goods or because of the 1929 stock market crash have little credibility among economists. However, most accept that flawed governmental policies were a primary cause.[192] Of special note, Nobel laureate Milton Friedman has long argued that "bad monetary policy" must shoulder much of the blame.[193] Another Nobel Prize winner, Robert Mundell, blamed the Depression on an attempt to reestablish the gold exchange standard after World War I "on too slender a gold base."[194] Similarly, economic historian Peter Temin argued that the roots of the Depression lay in a zealous adherence to the gold standard by Western nations after World War I even when the policy became deflationary.[195]

Fiscal policies made things worse. In the United States, the Ford-McCumber (1922) and Smoot-Hawley (1930) tariffs pushed rates to all-time highs. Other countries followed, resulting in a two-thirds reduction in world trade within three years.[196] Furthermore, New Deal policies had minor impact on ending the Depression. Although the U.S. money supply had fallen by one-third since 1929, for instance, Roosevelt insisted on maintaining high prices and wages. High unemployment

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[191] Robert A. Mundell, "Debt and Deficits in Alternative Macroeconomic Models," in *Debt, Deficit and Economic Performance*, eds. Mario Baldassarri, Robert Mundell, and John McCallum (New York: St. Martin's Press, 1993), 6-7 and 59.

[192] "A Survey of the 20th Century," *The Economist* 352, no. 8136 (11 September 1999), 12-21; "The World Economy," *The Economist*, 22; "Desperately Seeking a Perfect Model," *The Economist* 351, no. 8114 (10 April 1999), 69.

[193] For example, Milton Friedman, *Monetarist Economics* (Cambridge, Massachusetts: Basil Blackwell, 1991), 4-10.

[194] Mundell, "Debt and Deficits in Alternative Macroeconomic Models," 61-62 and 122.

[195] Peter Temin, *Lessons from the Great Depression: The Lionel Robbins Lectures for 1989* (Cambridge, Massachusetts: MIT Press, 1989), 7-8, 33, and 43-45.

[196] "A Survey of the 20th Century," *The Economist*, 12.

quite predictably continued. Furthermore, while Roosevelt's attempt to limit manufacturing output through the NRA failed, similarly inspired farm policies did not, and the nation witnessed the absurd spectacle of farmers getting paid to destroy crops while millions of Americans went hungry.[197] The situation would never have gotten so desperate or lasted so long had markets simply been allowed to operate. Recall as an example and as Bush admitted, the private sector's fast growing investment in research, which resulted in, among other things, a cornucopia of new electronic devices in the 1930s. Conditions did improve, perhaps due in part to the expansionist leanings of the New Deal, but notably after the U.S. effectively left the gold standard in 1933.[198] However, after being thwarted in his reach to have the NRA coordinate industry, Roosevelt switched course in 1935 and pushed programs, laws, and regulations inimical to business but more favored by his progressive base. These included the Wagner Act, which promoted unions, and the Social Security and Revenue Acts, which raised taxes. The "Roosevelt recession" resulted, and the Depression only ended with war.

Massive fiscal interventions by governments continued after the war. Theoretical underpinnings for the involvement came from John Maynard Keynes of Great Britain, the most influential economist of the twentieth century. According to Temin, Keynes agreed that monetary factors underlie the Depression,[199] but the more immediate problem was low investments by businesses. To make up for that, governments had to spend more. Politicians were persuaded, overcame the resistance of citizens (of Americans, that is), and complied.

Keynes actually advocated state intervention only as needed and temporarily. States should stabilize the economy without directly controlling it. When the private sector failed to invest sufficiently to maintain satisfactory performance, government had to spend on things like public works, even if that meant incurring a budget deficit. On the other hand, when investment by the private sector picked up, government should decrease spending. Keynes's disciples, who dominated Western economic policies through the 1970s, emphasized the former and often overlooked the latter. The legacy has been to saddle countries with inefficient and exorbitantly expensive state programs that are difficult to end or abate. Adopted to gain flexibility for government officials, Keynesian economic policies led to inflation, deficits, debt, and economic rigidity.[200]

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[197] Thomas Sowell, *Basic Economics: A Citizen's Guide to the Economy* (New York City: Basic Books, 2000), 33-34 and 215.
[198] Friedman, *Monetarist Economics*, 5; Mundell, "Debt and Deficits in Alternative Macroeconomic Models," 69-70 and 77; Temin, *Lessons from the Great Depression*, 96-98.
[199] Temin, *Lessons from the Great Depression*, 7.
[200] Yergin and Stanislaw, *The Commanding Heights*, 16-17 and 39-42.

State support of research meshed perfectly with postwar progressive, Cold War, and Keynesian thinking. To understand the impact of that sponsorship, British biochemist Terence Kealey studied relationships among science, technology, and economic progress, and stances government should assume on the former two to best foster the latter. His conclusions in *The Economic Laws of Scientific Research* make sense of long-ignored evidence. Specifically, Kealey examined statistics on civil (not defense) research for the OECD[201] nations and derived three economic laws of scientific research. His first law is as follows: "the percentage of national GDP spent (on civil research) increases with national GDP *per capita*." In other words, the richer a country, the more it spends on civil research, including all sources of funding. Countries spend on research when they can afford it, and because they must to remain competitive. Next, Kealey compared each country's percentage of GDP spent on civil research to the ratio of its business to government funding. This provided the basis for his second law: "public and private funding displace each other." That is, government-sponsored research does not simply add to what industry would otherwise do, but deprives it of money for its own research. Research is thus transferred from the private sector to government or its agents. The data indicate that the trade is to the disadvantage of total funding, unfortunately, as articulated by the third law: "public and private displacements are not equal: public funds displace more than they do themselves provide."

An obvious reason for the decrease is that governmental bureaucracy needed to administer research is expensive. More generally, new taxes must be imposed to cover costs of ever-expanding obligations that are not research, but which governments inevitably accrue. Also, nationalization of research raises the costs of entry for industry to conduct its own research. Industry after being taxed will do reduced amounts of research or, sometimes, none at all.[202] That is, some research can be all or nothing. Worse, government sponsorship substitutes the judgments of politicians for those of entrepreneurs and inventors. This is a mistake when economic progress is the goal, but it also means that industry may not participate in government-funded research it sees as unbeneficial.

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[201] OECD is an acronym for Organization for Economic Cooperation and Development. The organization includes the wealthiest capitalistic-tending countries. Kealey used historic data to 1985, when there were twenty-four OECD countries including the United States. He excluded Yugoslavia as not truly capitalistic. Yugoslavia is now an economic disaster, but in 1985 it had the best economy of any Eastern European nation. Kealey also excluded Luxembourg and Iceland as too small. Kealey, *The Economic Laws of Scientific Research*, 237. See also, "Table 10.1 Research statistics, OECD countries, 1985," 254-255. Five more countries have been admitted to the OECD in the 1990s. David Henderson, *The Changing Fortunes of Economic Liberalism: Yesterday, Today and Tomorrow* (London: Institute of Economic Affairs, 1998), 26-27.

[202] Kealey, *The Economic Laws of Scientific Research*, 245-250.

All this applies to basic research by itself. A linear model of economic progress, in which basic research leads to new technologies that lead to economic growth, is too simplistic, and Bush likely knew it.[203] For one thing, there are no clear dividing lines between technology and science or applied and basic research. Furthermore, research, development, and economic progress derive in complex ways, and the relationships are better modeled as an interconnected network with numerous feedback loops.[204] For example, new science often sprouts from new technology, as in the case of steam engines leading to the science of thermodynamics. The Big Bang theory of the creation of the universe began with two Bell Laboratory technicians inexplicably finding background radiation in microwave transmissions.[205] The transistor is an instance of creativity going both directions, since it involved quantum mechanics, but initial developments did not wait. Moreover, the need to understand transistors resulted in solid-state physics.

As Project Hindsight found, most new technology comes from old technology, but industry will nonetheless invest in basic research. Economists have found that industry performs basic research for the simple reason that it pays. The more basic research industry does, the greater its increases in productivity.[206] Kealey believed that industry does not so much benefit directly from basic research as from what he called secondary-mover advantages. Industry hopes for scientific breakthroughs to exploit, of course, but the main reason it funds basic research is to keep its scientists abreast of what others are doing. That is, as scientists conduct research, they read scientific journals and learn about other research, thereby greatly increasing odds of uncovering useful information.[207] Furthermore, industry will fund basic research at universities for the problem solving skills it teaches students it hopes to employ.[208] Overall evidence therefore suggests that without government interference more, not less, technology would have resulted and of higher commercial quality. It is fortunate for Americans that governments of other countries have pursued much the same wasteful policies of funding research as their government.

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[203] Zachary, *Endless Frontier*, 219.
[204] "A Survey of Innovation in Industry," *The Economist* 350, no. 8107 (20 February 1999), 8-11.
[205] Kealey, *The Economic Laws of Scientific Research*, 63-70 and 216-219.
[206] Edwin Mansfield, "Basic Research and Productivity Increase in Manufacturing," *The American Economic Review* 70, no. 5 (December 1980), 871; Zvi Griliches, "Productivity, R&D, and Basic Research at the Firm Level in the 1970s," in *R&D and Productivity: The Econometric Evidence* (Chicago: University of Chicago Press, 1998), 98.
[207] Kealey, *The Economic Laws of Scientific Research*, 224-232.
[208] "A Survey of Innovation in Industry," *The Economist*, 11.

How unfortunate it is that Adam Smith has been forgotten, or more exactly, misconstrued. Much waste and misery could have been avoided. Smith's minimalist philosophy is synonymous with *laissez faire* (a term he did not use), but with interventionist government in favor, he has been wrongfully dismissed as either an apologist for big business or hopelessly out-of-date. For example, it is commonly asserted that free-market policies might have been viable in eighteenth-century Britain, supposedly a simple world of independent shopkeepers, but are inadequate to protect consumers in an age of complexity and oligopolistic corporations. However, there is no reason to think free-market policies are not at least as appropriate in a complex society as a simple one. It is likely that the clout of consumers increased with the proliferation of choices that capitalism (another word Smith did not use) made available. While there may have been proportionally more butchers and bakers in the eighteenth century, it is doubtful consumers enjoyed more choices. It would have been as difficult to walk the extra blocks to a second butcher as it is today to drive the extra miles to a competing supermarket. Nor were people necessarily more independent. Smith recorded that the preponderance of laborers, including in agriculture, served "under a master" even in his time before giant industry.[209] Furthermore, the enormous turnover among major U.S. corporations suggests competition is greater than assumed.[210]

Contrary to reputation, if *Wealth of Nations* had an overriding theme, it was to protest the numerous combinations and monopolies of the time. Moreover, if Smith had a bias, it was not to the capitalist, but to the consumer. "Consumption is the sole end and purpose of all production," opined the admirable Smith, "and the interest of the producer ought to be attended to, only so far as it may be necessary for promoting that of the consumer." Smith found instead that businessmen often became rich by "oppression of the poor" and contriving laws against consumers. In that skullduggery, they had the assistance of, "that insidious and crafty animal, vulgarly called a statesman or politician, whose councils are directed by the momentary fluctuations of affairs." Politicians and businessmen got little sympathy from Smith. He commented caustically, for example, that merchants and manufacturers were, "silent with regard to the pernicious effects of their own gains. They complain only of those of other people." As for government officials: "They are themselves always, and without any exception, the greatest spendthrifts in the society. Let them look well after their own expence, and they may safely trust private people with theirs. If their own extravagance does not ruin the state, that of their subjects never will." Smith actually thought merchants and manufacturers unproductive. He argued nonetheless that fewer restraints placed upon them by government would

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[209] Smith, *Wealth of Nations*, 67.
[210] Editors of *Forbes*, "Steel versus Silicon," *Forbes* 160, no. 1 (7 July 1997), 130.

result in greater competition and cheaper goods. Smith promoted a free-market orientation to best serve most people, even as it undermined entrenched interests. He acknowledged that government might establish a particular industry sooner than it otherwise could be created. Still, he believed the overall wealth of a nation was best served by investment seeking its natural ends. Without regulations erected against free trade: "the private interests and passions of men naturally lead them to divide and distribute the stock of every society, among all the different employments carried on in it, as nearly as possible in the proportion which is most agreeable to the interest of the whole society."

Critics insist that capitalism exploits labor, but it did not mean that for Smith. It was the "skill, dexterity, and judgment," of active workers, after all, which constituted the true wealth of nations. Manufacturers should treat labor well partly out of fairness: "It is but equity, besides, that they who feed, cloath and lodge the whole body of the people, should have such a share of the produce of their own labour as to be themselves tolerably well fed, cloathed and lodged." Smith believed people had natural empathy with others, and was a philanthropist himself, but rather than appeal to the kindness of manufacturers, he asserted that they had selfish reasons to pay labor generously: "Where wages are high, . . . we shall always find the workmen more active, diligent, and expeditious, than where they are low." High wages were more than compensated by productivity increases, many deriving from labor, "inventing the most proper machinery for executing the work."

Smith had great confidence in people. *Wealth of Nations* resonated with the same optimism as its contemporary, the Declaration of Independence. Both implied limited government. Where Thomas Jefferson wrote of "certain unalienable rights," including "life, liberty, and the pursuit of happiness," Smith had his "invisible hand," the belief that free people on their own organize their activities to best serve society, even if unintentional. And where the American document declared, "all men are created equal," Smith more verbosely but similarly claimed, "The difference of natural talents in different men is, in reality, much less than we are aware of; and the very different genius which appears to distinguish men of different professions, when grown up to maturity, is not upon many occasions so much the cause, as the effect of the division of labour."

Smith believed inventions typically resulted because workmen sought to lighten their labors by leveraging the benefits of division of labor. Factories, he reported, were full of, "very pretty machines, which were the inventions of such workman, in order to facilitate and quicken their own particular part of the work." He thought a second source of innovations came from, "the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade."

Division of labor allowed some people to specialize in engineering. Others combined "together the powers of the most distant and dissimilar objects" to increase "the quantity of science."

The implication is that Smith saw science as important but not deserving of privilege. Taken in total, "the great multiplication of the productions of all the different arts" brings, "in a well-governed society, . . . universal opulence that extends itself to the lowest ranks of the people." In short, free people in a free society will invent and produce and everyone will prosper. History bears him out.

Not least among Smith's virtues was pragmatism. Free markets served society best but could never be realized fully. To expect a society to adopt such policies wholeheartedly, according to Smith's famous assessment, "is as absurd as to expect that an Oceana or Utopia should ever be established." The "prejudices of the public" would be against it, and governments had no choice but to accede to those prejudices. Worse, "the private interests of many individuals irresistibly oppose it." By this he meant merchants and manufacturers, who, "like an overgrown standing army, . . . have become formidable to the government, and upon many occasions intimidate the legislature." A government official who supported big business was, "sure to acquire not only the reputation of understanding trade, but great popularity and influence with an order of men whose numbers and wealth render them of great importance." If that official opposed big business, on the other hand, "neither the most acknowledged probity, nor the highest rank, nor the greatest public service, can protect him from the most infamous abuse and detraction." In short, governments tended to collude with businesses in using their combined powers against consumers. Smith believed ordinary people gained countervailing power to the extent they insisted on free-market policies.

True to his practical nature, Smith wisely understood that government could never be made perfect but recognized its necessity. Government should be kept to a minimum but nonetheless had important roles to play. Among its duties, government must provide the legal framework to ensure effective functioning of competitive markets and protection of private property. It needed to provide for defense and the "dignity of the sovereign." Government also must take responsibility for public works, but Smith thought most such projects could be made to defray their own costs. On the other hand, he worried that division of labor, for all the good that comes from it, could have the effect of rendering people stupid. Government should therefore take action to ensure that everyone acquired at least the fundamentals of an education. "Invention is kept alive," in this way, "and the mind is not suffered to fall into that drowsy stupidity."[211]

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[211] Smith, *Wealth of Nations*, 3, 11-12, 17, 80, 83, 88-89, 97, 100, 146, 152, 227, 238, 240-241, 306, 338-339, 346-347, 357, 375, 388, 446-449, and 481; Sowell, *Basic Economics*, 305.

In summary, during the nineteenth century the *Wealth of Nations* increasingly served "as a court of appeal on matters of economics and politics,"[212] and free markets reached their apogee. The next century turned to government intervention guided by experts. That appeared to work for a time, but nonetheless, nations that prospered most had democratic governments that meddled least. States fostered new technologies, and indeed, it could be argued that few became viable in the last half of the twentieth century without that support, so pervasive did government become. Still, weight of evidence suggests that direct involvement by government has a dampening effect overall on emerging technologies. At one extreme, for example, the Soviet Union attempted to eliminate market mechanisms. It was characterized by horrendous human rights abuses, but try mightily as it did, showed little propensity for innovation and ultimately failed. To the other extreme, Great Britain and the United States were invention powerhouses in the nineteenth century. They lost ground as they evolved from *laissez-faire* capitalism into mixed economies, Great Britain more than America as it became more socialistic. Evidence thus points to a correlation between economic freedom and innovation, and also with standard of living and human rights.

The case in point is the electronic digital computer, on the cusp of reality by private interests on the eve of World War II, both as a tool of applied mathematics and for information processing. Turing had articulated its theory and Atanasoff and Berry much of its essential technology. It all came together, one might say, with the human brain in mind and under von Neumann after the war, but certainly would have happened anyway. The computer was not the product of a few geniuses, but of many. Leibniz, Babbage, Patterson, Hollerith, Watson Sr., Bryce, Bush, W. J. Eckert, Stibitz, Shannon, and Zuse were other major figures prewar. Countless others contributed in anonymity or near-anonymity. However, if the history of computing is a history of genius, so is the history of technology generally, although inventors usually are not otherwise regarded as exceptional people. Adam Smith had it right: Ordinary people have extraordinary ingenuity given the inclination, and *laissez-faire* capitalism provides the best environment to bring it to fruit.

On the other hand, government promotes not only inefficiency, but also mediocrity. An example was the ENIAC. Huge, clunky, costly, and ineffectual, it stood as a fitting metaphor of the government that created it, as if in its own burgeoning image. Designers of subsequent computers returned to fundamental principles: smaller is better but compromise is necessary. The United States was founded on those same principles, but advocates for the federal government have found ever more excuses to expand its suffocating powers.

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[212] Ashton, *The Industrial Revolution*, 17

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