Herman H. Goldstine received his Ph.D. from the University of Chicago in 1936, writing a thesis in functional analysis under the guidance of Lawrence M. Graves. After holding a faculty position at the University of Michigan, he went to the Institute for Advanced Study in 1946 to work on the electronic computer project with John von Neumann. Later he served as a Director of Scientific Development at I.B.M. Since 1984 he has been Executive Officer of the American Philosophical Society. Dr. Goldstine has taken a special interest in the history of computers and is the author of The Computer from Pascal to von Neumann.

A Brief History of the Computer

HERMAN H. GOLDSTINE

Rather curiously the first digital calculator was designed and built by Wilhelm Schickard (1592–1635) in the small university town of Tübingen in southern Germany during the Thirty Years' War. Schickard was professor of astronomy, mathematics, and Hebrew and also a friend and colleague of Kepler, the great astronomer of the era. In fact they had been fellow-students of Maestlin. What little is known of Schickard's invention was not uncovered until 1957 when two letters from Schickard to Kepler were found describing a machine Schickard designed and built in 1623 to do completely automatically the operations of addition and subtraction and partly automatically those of multiplication and division.[1]

The first letter, dated 20 September, 1623, to Kepler says:

> [This machine] ... immediately computes the given numbers automatically, adds, subtracts, multiplies, and divides. Surely you will beam when you see how [it] accumulates left carriers of tens and hundreds by itself or while subtracting takes something away from them...

[1] For a fairly comprehensive discussion of the period covered by this paper see H. H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, 1972).

The second letter, dated 25 February, 1624, is a sadder one. It says:

> I had placed an order with a local man, Johann Pfister, for the construction of a machine for you; but when half finished, the machine, together with some other things of mine, especially several metal plates, fell victim to a fire which broke out unseen at night .... I take the loss very hard, now especially since the mechanic does not have time to produce a replacement soon.[2]

Unhappily Schickard, his family, and his machine were destroyed by the fire and plague which swept through southern Germany at that time, and no record of his work remained for posterity to read or to see. It is interesting to speculate upon the question of what Kepler would have done had he used Schickard's machine for his calculations. It was in the same year as Schickard's second letter, 1624, that Kepler brought out his first table of logarithms. In fact in 1618 Kepler already had written a letter to Napier, the inventor in 1614 of logarithms, in which he expressed his high regard for Napier's tables.

While we might *a priori* think that Kepler would have given up his use of logarithms in favor of the digital approach of counting, it seems to me very unlikely. The first machines were almost certainly quite slow and the operator of one would have had considerable trouble in keeping up with a skilled user of logarithms. But we can of course not know, and it is perhaps idle to speculate on this point further.

In any case the next development in our tale was made by Blaise Pascal (1623–1662) in complete ignorance of Schickard's device; Pascal built a very elegant machine for addition and subtraction in 1642–1644. Actually he made several copies of his instrument somewhat later which are still extant in a number of cities including Paris, London, and New York. The machine was considered to be quite important by the scientific community, and it is described in detail by Diderot.[3] Pascal built it as an act of filial piety to aid his father, who, as a high civil servant, was busy reorganizing the tax structure of Basse-Normandie.

About thirty years later Leibniz took up Pascal's ideas and ingeniously perfected them by a device now called the *Leibniz wheel.* To the Pascal machine, as improved by him, Leibniz added an automatic multiplier–divider unit and thus created a prototype for a whole line of calculators that culminated in the electromechanical desk machines of World War II. These are the ones

[2] B. von Freytag-Löringhoff, "Wilhelm Schickards Tübinger Rechenmaschine von 1623 in Tübinger Rathaus," *Kleine Tübinger Schriften*, Heft 4: pp. 1–12. See also von Freytag, "Über der erste Rechenmaschine," *Physikalische Blätter* **41** (1958): pp. 361–365.

[3] D. Diderot, *Encyclopédie ou Dictionnaire Raisonné des Sciences, des Arts et des Métiers* **1** (Paris, 1751): pp. 680–740. This is in the article on Arithmetic. Diderot calls this the first digital machine.

that have been displaced by our now ubiquitous pocket calculators. Interestingly Leibniz tried to persuade the Tsar Peter the Great to send a copy of this machine to China to impress the emperor in the hopes of encouraging East–West trade. In this attempt Leibniz was unsuccessful since the tsar was preoccupied with other more pressing problems.

It was Leibniz who clearly understood the true goal of computer designers. He wrote:

> Also the astronomers surely will not have to continue to exercise the patience which is required for computation. It is this that deters them from computing or correcting tables, from the construction of Ephemerides, from working on hypotheses, and from discussions of observations with each other. For it is unworthy of excellent men to lose hours like slaves in the labor of calculation which could safely be relegated to anyone else if machines were used.

Little further progress was made towards Leibniz's goal until the early days of the nineteenth century when an eccentric Englishman, Charles Babbage, who held Newton's old chair in mathematics at Cambridge, realized the great need to automate the calculation of the British *Nautical Almanac.* (This is a set of tables produced annually which contains data *inter alia* enabling a mariner to locate his position in longitude at sea.) These tables were first introduced in 1767 and constituted a great advance for the Royal Navy since it made possible exact knowledge of the position of ships at sea. Babbage as one of the founders of the Royal Astronomical Society was much concerned with the problem of calculating these astronomical tables with speed and accuracy.

He proposed in 1823 to the government that he be given a grant to build what he called a *Difference Engine.* This was to be a device that could by the simple arithmetical operations of addition and subtraction take a very small number of manually performed mathematical calculations and from them construct a complete printed nautical almanac. By 1827 this project was still not completed and Babbage had a breakdown which caused him to travel on the Continent. When he returned, he received another grant but by 1842 the government quashed the project. Robert Peel remarked sarcastically that "I would like a little previous consideration before I move in a thin house of country gentlemen a large vote for the creation of a wooden man to calculate tables for the formula $x^2 + x + 41$." Some working pieces of this machine of Babbage are on exhibit in the Science Museum in London.

A remarkable Swedish gentleman, Pehr Georg Scheutz (1785–1873), built a working copy of Babbage's machine from an article in the *Edinburgh Review* and some help from Babbage and displayed it in London in 1854. This machine is now on exhibit at the Smithsonian Institution and a copy was made for the registrar-general in London where it did much valuable work up until 1914. Scheutz himself was a remarkable virtuoso, being an editor of the Stockholm newspaper, *Aftenbladet*, and the translator of Boccaccio, Shakespeare, and Walter Scott into Swedish. Trigonometrical tables printed by his machine and dedicated by him and his son to Babbage are in the library of Brown University.

In 1833 Babbage conceived the basic idea for his chief work, which he called the *Analytical Engine*. It was to be a machine in concept in some ways like the modern general purpose computer, and its basic idea was derived by him from an insight he gained studying the Jacquard attachment to the loom. Babbage never finished his machine, and it was not until a century later that his ideas were given concrete realization. In fact during the Second World War, the International Business Machines Corporation and Harvard University collaborated on the development and production of an electro-mechanical computer which was reviewed in *Nature* under the title "Babbage's Dream Come True."[4]

Joseph Marie Jacquard in 1805 had invented an ingenious system of punch cards and hooks to move threads so that exceedingly elaborate damask patterns can be woven at little cost. To do this he saw that he could automate the execution of the pattern or program used by weavers in a relatively simple way. Jacquard used cards with holes in certain predetermined places so arranged that they reproduced the desired pattern. Through the holes, hooks can pass and displace threads of the warp so that the shuttle can move over and under the correct threads. Babbage wrote:

> It is known as a fact that the Jacquard loom is capable of weaving any design that the imagination of man may conceive... holes [are punched] in a set of pasteboard cards in such a manner that when these cards are placed in a Jacquard loom, it will then weave ... the exact pattern designed by the artist.
>
> Now the manufacturer may use, for the warp and weft of his work, threads that are all of the same colour; let us suppose them to be unbleached or white threads. In that case the cloth will be woven all in one colour; but there will be a damask pattern upon it such as the artist designed.
>
> But the manufacturer might use the same card, and put into the warp threads of any other colour. Every thread might even be of a different colour, or of a different shade of colour; but in all these cases the *form* of the pattern will be precisely the same—the colours only will differ.

[4]L. J. Comrie, *Nature* **158** (1946): pp. 567–568.

The analogy of the Analytical Engine with this well-known process is nearly perfect.

The Analytical Engine consists of two parts:–

1st. The store in which all the variables to be operated upon, as well as all those quantities which have arisen from the results of other operations, are placed.

2nd. The mill into which the quantities about to be operated upon are always brought.

Every formula which the Analytical Engine can be required to compute consists of certain algebraical operations to be performed upon given letters, and of certain other modifications depending on the numerical value assigned to those letters.

There are therefore two sets of cards, the first to direct the nature of the operations to be performed—these are called operation cards; the other to direct the particular variables on which those cards are required to operate—these latter are called variable cards.

Under this arrangement, when any formula is required to be computed a set of operation cards must be strung together, which contains the series of operations in the order in which they occur. Another set of cards must then be strung together, to call in the variables into the mill, in the order in which they are required to be acted upon. Each operation will require three other cards, two to represent the variables and constants and their numerical values upon which the previous operation card is to act, and one to indicate the variable on which the arithmetical result of this operation is to be placed.

The Analytical Engine is therefore a machine of the most general nature. Whatever formula it is required to develop, the law of its development must be communicated to it by two sets of cards. When these have been placed, the engine is special for that particular formula.

Every set of cards made for any formula will at any future time, recalculate that formula with whatever constants may be required.

Thus the Analytical Engine will possess a library of its own. Every set of cards once made will at any future time reproduce the calculations for which it was first arranged. The numerical value of its constants may then be inserted.[5]

[5]C. Babbage, *Passages from the Life of a Philosopher* (London, 1864; reprinted 1968), pp. 117ff.

This serves perhaps very well to describe Babbage's conception. Unhappily it died with him and remained lost to those of us who came later. He never succeeded in completing his instrument, in part at least for lack of an adequate technology in his time; but also his machine, even if workable, would not have been very useful since it would have been too slow.

Perhaps it is relevant to quote what Lord Moulton wrote on Babbage's work in 1915:

> One of the sad memories of my life is a visit to the celebrated mathematician and inventor, Mr. Babbage. He was far advanced in age, but his mind was still as vigorous as ever. He took me through his workrooms. In the first room I saw the parts of the original Calculating Machine, which had been shown in an incomplete state many years before and had even been put to some use. I asked him about its present form. "I have not finished it because in working at it I came on the idea of my Analytical Machine, which would do all that it was capable of doing and much more. Indeed, the idea was so much simpler that it would have taken more work to complete the Calculating Machine than to design and construct the other in its entirety, so I turned my attention to the Analytical Machine." After a few minutes' talk we went into the next workroom, where he showed and explained to me the working of the elements of the Analytical Machine. I asked if I could see it. "I have never completed it," he said, "because I hit upon an idea of doing the same thing by a different and far more effective method, and this rendered it useless to proceed on the old lines." Then we went into the third room. There lay scattered bits of mechanism, but I saw no trace of any working machine. Very cautiously I approached the subject, and received the dreaded answer, "It is not constructed yet, but I am working at it, and it will take less time to construct it altogether than it would have taken to complete the Analytical Machine from the stage in which I left it." I took leave of the old man with a heavy heart. When he died a few years later, not only had he constructed no machine, but the verdict of a jury of kind and sympathetic scientific men who were deputed to pronounce upon what he had left behind him, either in papers or mechanism, was that everything was too incomplete to be capable of being put to any useful purpose.[6]

In leaving Babbage I would be totally remiss were I not to mention the world's first programmer, Augusta Ada Byron. She was Lord Byron's only child and was separated from him when she was but a month old, at which

[6] Lord Moulton, "The Invention of Logarithms, Its Genesis and Growth," *Napier Tercentenary Memorial Volume*, ed. C. G. Knott (London, 1915), pp. 19–21.

time he left England forever. Each of them died at age thirty-six, and they lie together in the Byron vault in Nottinghamshire. Byron had great affection for her and wrote of her in Canto III of his Childe Harold's Pilgrimage:

My daughter! with thy name this song begun—
My daughter! with thy name thus much shall end—
I see thee not,—I hear thee not,—but none
Can be so wrapt in thee; thou art the friend
To whom the shadows of far years extend:
Albeit my brow thus never shouldst behold,
My voice shall with thy future visions blend,
And reach into thy heart,—when mine is cold,—
A token and a tone even from thy father's mould.

In any case as the Countess of Lovelace she did very much for Babbage and among other things programmed the calculation of the so-called Bernoulli numbers for his never-to-be-finished computer. Her description of Babbage's machine is perhaps worth repeating: "We may say most aptly that the Analytical Engine weaves *algebraical patterns* [her italics] just as the Jacquard-loom weaves flowers and leaves. Here, it seems to us, resides much more of originality than the Difference Engine can be fairly entitled to claim."

At this point it is perhaps worth noting that there were three large and distinct trends discernible in computing: the astronomical one, which was the oldest, calling for great accuracy but only moderate speed; the physical one, calling for small accuracy but for great speed; and the commercial one, which was the newest, calling for complete accuracy but moderate speed. The astronomers and businessmen by their need for accuracy were almost exclusively interested in digital computation whereas physicists by their need for speed went the route of analog or measurement computation using devices such as logarithmic tables, slide rules, etc. There is hardly space here to discuss such instruments. Instead let it suffice to say that the modern digital computer served for the first time to satisfy the diverse needs of the three constituencies mentioned above. Indeed this blending of separate markets into a common one may very well be one of the early milestones in the industrial success of the modern computer.

In the days just before the 1890 census a young engineer Herman Hollerith (1860–1929), working at the suggestion of a man of great wisdom and intellectual breadth, John Shaw Billings (1839–1913), invented machines for recording, reading, and sorting data entered upon punch cards. Hollerith designed and built a sorting machine that used boxes he bought from the United States Mint. They originally held paper currency, and thus the size of the punch card was standardized by Hollerith at 6 5/8 by 3 1/4 inches since these were the dimensions of our old dollar bills.

This equipment was of greatest value in the 1890 census and very quickly became the accepted tool for handling censuses in virtually every civilized country. Soon after this Hollerith left the Census Bureau to found a company which ultimately became the International Business Machines Corporation; meanwhile the management of the Census Bureau at the newly founded National Bureau of Standards established a Research and Development Laboratory under the direction of James Powers to build equipment competitive with Hollerith's. Powers successfully did this and also went into business for himself. His company ultimately became the Sperry-Rand Corporation. Thus we see two of the leaders in the modern computer field emerging from the application of digital computation to business. The adaptation of these business-oriented machines to astronomy was to take place in the 1930s and was carried out partly in England by L. J. Comrie, then superintendent of HM Nautical Alamanac Office, and very completely in the United States somewhat later by W. J. Eckert of Columbia University and IBM.[7]

During the First World War largely through the efforts of Oswald Veblen, then professor of mathematics at Princeton University and later at the Institute for Advanced Study, and of Forrest R. Moulton, then professor of astronomy at the University of Chicago and later secretary of the American Association for the Advancement of Science, groups of eminent astronomers and mathematicians were formed in what is now the Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, and in the Office of the Chief of Ordnance, Washington, D.C. The men in these groups put ballistics on a sound scientific basis and introduced sophisticated calculational ideas borrowed from astronomy into the subject. This tradition was so strong that it survived miraculously intact until the start of the Second World War when Veblen became the chief scientist at Aberdeen and Professor Marston Morse at Washington, D.C., where they again formed first-rate scientific groups. It was out of this that the electronic revolution in computing took place because when the proper time came they were ready to give their backing and support to the enterprise.

In fact Veblen not only brought to Aberdeen a full-time staff of leading astronomers, mathematicians, and physicists, but he also formed a scientific advisory committee which contained among others John von Neumann of the Institute for Advanced Study, who is in many ways the hero of this account. Von Neumann, a mathematician, was at this time a consultant not only to Aberdeen but also to the Los Alamos Scientific Laboratory. At the latter place he was intellectual leader of an activity to design what is called an implosion type device, and to this end became deeply interested in calculational machines and techniques. In fact one of his greatest contributions to the computer field was to show the scientific community how very complex physical situations could be reduced to computational form and hence studied

[7]See W. J. Eckert, *Punched Card Methods in Scientific Computation* (New York, 1940).

by numerical means. In effect he showed how to simulate problems mathematically, solve them computationally, and then express the results back into meaningful physical terms. Even though this may sound commonplace today, it was not so four decades ago.

The computing activity at Aberdeen had become so large in World War II as compared to that in World War I that the relevant officers of the Ordnance Department found it desirable to establish a substation of the Aberdeen Proving Ground at the Moore School of Electrical Engineering, University of Pennsylvania. The University appointed Professor J. Grist Brainerd to act as its liaison with the government, and the army appointed me to head this substation where I had the pleasant task of working with Brainerd. One of the activities the university undertook was the training of young women to be calculators either in Philadelphia or Aberdeen. The teachers for this group were Adele Goldstine, my late first wife, Mildred Kramer, and the late Mary Mauchly.

However effective all this human help was, there was simply not enough computing power available to Army Ordnance to do all that it was responsible for, and therefore I was quite anxious to find some real solution to this problem. To this end early in the spring of 1943 Professor Brainerd formally proposed to me on behalf of the university that the Moore School would be willing to undertake the design, development, and construction of an electronic digital computer for the army. This proposal was based upon ideas generated by John W. Mauchly, then a young faculty member in the Moore School, and represented an amalgam of his thinking and that of Professor John V. Atanasoff, then of Iowa State College. This proposal was enthusiastically accepted, and by June 1, 1943, the Moore School officially started work on what was to be the first general-purpose electronic computer, the ENIAC — Electronic Numerical Integrator and Computer. The project was under Brainerd's general direction and was fortunate in having for its chief engineer a brilliant young student, J. Presper Eckert, Jr. This machine was finished by the end of 1945 and was formally dedicated in February of 1946 at which time it was doing useful work for the government.

It was in the summer of 1944 that von Neumann became aware of the ENIAC project when we met one another on a railroad platform in Aberdeen, and from that point on until his untimely death in 1957 his career was profoundly influenced by the computer and the computer by him. Shortly after this time a group of us at the Moore School including von Neumann began the logical design of a machine called the EDVAC to be a successor to the ENIAC, which even though not yet completed, was known by us to be obsolescent in the light of the very rapid advances in electronics resulting from the developments of radar and of fire-control devices. This machine was finished after the war was over but only after the British had built a similar one in 1949 at Cambridge known as the EDSAC under the direction of Maurice Wilkes.[8]

Von Neumann and I in the meantime set up at the Institute for Advanced Study a three-phased project more or less competitive with that at the University of Pennsylvania on the EDVAC to try to test out some other ideas on how an electronic machine should be designed. This was done partly in cooperation with Dr. Vladimir Zworykin of the Radio Corporation of America Princeton Laboratories and Professor John W. Tukey of Princeton University. One phase of the project was concerned with mathematics and computer architecture; it involved the logical design of a computer as well as the study of new mathematical techniques that would be needed for the new computers. A second was concerned with engineering and involved the actual development and construction of the computer. The third was concerned with the development of techniques to calculate from the so-called hydrodynamical equations of the atmosphere the weather across the United States for twenty-four-hour periods.

All three projects were quite successful. Of the first it has been said:

> Who invented stored programming? Perhaps it doesn't matter much to anyone other than the principals involved just who gets the credit ....
>
> Nevertheless the paper reprinted here is the definitive paper in the computer field. Not only does it specify the design of a stored program computer, but it anticipates many knotty problems and suggests ingenious solutions ....

This was a description of a paper by A. W. Burks, H. H. Goldstine, and J. von Neumann. In addition to the logical design work we wrote a number of other papers which defined and analyzed programming as well as modern numerical analysis.

Of the second project it has been said that "[a] machine... (variously known as the IAS, or Princeton, or von Neumann machine) was constructed and copied (never exactly) and the copies copied ...."[9] It became the prototype for the computers of today. Of the third it was noted that out of its work under the direction of Jules Charney have come the techniques used by virtually every national weather bureau for daily prediction.

As we saw above, the British became very active in the computer field, in part at least through the instrumentality of Douglas Hartree, then professor

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[8] M. V. Wilkes, Early computer development at Cambridge: The EDSAC, *The Radio and Electronic Engineer*, Vol. 45, 1975, pp. 332–335. Prof. Thomas Gold, now of Cornell University but then just returned to Cambridge (England) from the Admiralty Signals Establishment, "...was able to give me the essential parameters of a design [for the store]...[I] found that, indeed it did work very well" (p. 333).

[9] Paul Armer, *Datamation* **8** (1962).

at Manchester and later at Cambridge. He had been brought by us to the Moore School during the war so that we could "spread the good word" to our allies. The next to become interested were the Swedes. Their government sent Professor Stig Ekelöf of Gothenburg on an exploratory trip that resulted in the later arrival in the United States of a group of young engineers and physicists to learn what was being done. From these visits resulted several excellent computers including Dean Carl-Erik Froeberg's SMIL at the University of Lund, and Professor Erik Stemme's BESK at the Royal Institute of Technology in Stockholm.[10]

Perhaps it is worth telling Ekelöf's reaction to his visit to see the ENIAC in the fall of 1946:

> However I am afraid I am still on the same level as the old man in those years when the electric light began, who understood everything quite well except one thing—how the oil could pass through the fine wires!!! ...
>
> There is an enormous interest in Sweden right now for these machines. If the ENIAC were for sale and if it were a good idea to buy it (which I understand it is not!) then we would certainly have the money available. Probably some young people will be sent out shortly to acquaint themselves with this new field.[11]

The Austrians and the Germans soon afterwards became active and produced several machines, as did many other countries.

But space does not permit us to go into any more detail. Instead we should now summarize the most important early steps in the modern computer revolution:

1. The adaptation in the 1940s of the electronic medium to computation, since it produced a hundred-fold "speed-up" in computation. A calculation that before would have taken two years to do with the best electro-mechanical equipment of the 1940s could then be done on the ENIAC in about a week. Thus tasks previously impossible become possible and even trivial in some cases.

2. The invention of the stored program and of the techniques for programming as well as the development of modern numerical analysis, since these made it possible to handle virtually any problem on a computer that could be described in a finite mathematical essay properly written.

3. The invention of the coincident-current magnetic core memory by Professor Jay Forrester of the Massachusetts Institute of Technology and Dr. Jan

[10]SMIL is the Swedish for "smile" and stood for *Siffersmaskinen I Lund* (Digital machine of Lund). BESK is the slang word for "beer" and means "bitter" and stood for Binär Electronisk Sekvens Kalkylator (Binary, electronic, sequenced calculator).

[11]Letter, Ekelöf to Goldstine, 9 November, 1946.

Rajchman of the Radio Corporation of America, since this device allowed computers to be built which had very great storage capacities.

4. The invention of the transistor by Professor John Bardeen, Walter H. Brattain, and William Shockley, who were then all of the Bell Telephone Laboratories, since this greatly increased the reliability of machines and has ultimately led to the wonderful new miniaturized circuits.

5. The standardization and mass production of computers by American industry, since this made it possible for the world at large to use these machines and obviated the need for "do-it-yourself" construction.

6. The invention of FORTRAN, a universal language for computers, by Dr. John Backus of IBM, since it served to make scientific intercommunication between practitioners of computer science possible and profitable technically.

Perhaps we should close with a few lines from Tennyson's *Locksley Hall*:

> Here about the beach I wander'd, nourishing a youth sublime
> With the fairy tales of science, and the long result of Time
> When the centuries behind me like a fruitlike land reposed;
> When I clung to all the present for the promise that it closed;
> When I dipt into the future far as human eye could see;
> Saw the Vision of the world, and all the wonder that would be.—