# A Chronology of Digital Computing Machines To 1952

## Mark Brader

For some time Mark Brader has maintained a chronology of digital computing machines. Resulting from a break in his Internet access, Mark is no longer posting updates regularly to Usenet; instead, I am maintaining this copy on the WWW for him. This page is based on his final posting of the chronology, but has undergone subsequent updating and minor editing.

A Chronology of Digital Computing Machines (to 1952)

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As I am leaving SoftQuad (and Usenet, at least for the moment) today, I thought I would take this opportunity to repost the current version of the following article which I have been maintaining and which has appeared several times in these newsgroups.

Followups this time are directed to soc.history.science; if someone else wants to grab this document and take over maintenance of it, they are welcome to do so. As it says at the end, it's in the public domain.

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[Canned article follows -- last substantively modified June 8, 2000.]

[This article was prepared using the ISO 8859-1 character set. If you see an i-circumflex in "naquît" and a u-umlaut in "Tübingen", that's correct. If not, be aware that several other words and names here and there through the article will also look wrong for you. This should not be an issue with the WWW version of this document.]

What was the first computer and who built it?

It turns out that this is more a question of definition than a question of fact. The computer, as we now understand the word, was very much an evolutionary development rather than a simple invention. This article traces the sequence of the most important steps in that development, and in the earlier development of digital calculators without programmability. It may help you to decide for yourself whether you think the first computer was the ABC, the Z3 (aka V3), the ENIAC, the SSEC, the Manchester Mark I (aka Baby), the EDSAC, or perhaps yet another machine -- and how to apportion the honor of invention among John Atanasoff, Charles Babbage, Presper Eckert, John Mauchly, Alan Turing, John von Neumann, Konrad Zuse, and others.

# A Chronology of Digital Computing Machines To 1952

**Mark Brader**

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This article has evolved from an original version that I drafted in 1988, and has been posted to various Usenet groups several times. It has been prepared primarily from two sources:

> "Bit by Bit: An Illustrated History of Computers" by Stan Augarten
> 1984, Ticknor and Fields, New York
> ISBN 0-89919-268-8, 0-89919-302-1 paperback

> "A History of Computing Technology" by Michael R. Williams
> 1985, Prentice-Hall, Englewood Cliffs, NJ
> ISBN 0-13-389917-9

Either of these books is well worth a trip to the library to read. (Unfortunately, finding either one in a bookstore today would be an unlikely proposition.) Augarten is a journalist; he writes very readably, but occasionally does not say exactly what he means. Williams is a computer science professor; his book is superior in technical depth, and covers additional subject areas including analog computing and computing in ancient times.

For some material I also consulted the following books.

> "The Dream Machine: Exploring the Computer Age"
> by Jon Palfreman and Doron Swade
> 1991, BBC Books, London
> ISBN 0-563-36221-9

The book of the TV series of the same title, which changed to "The Machine that Changed the World" when it was shown in the US on PBS. I enjoyed the content but found the typographic design so hideously mannered as to be distracting. This book has less technical detail than the two mentioned above, and a greater emphasis on the impact of computers on the modern world; a considerable fraction of its length is about the uninteresting :-) period after the end of this chronology.

> "Portraits in Silicon" by Robert Slater
> 1987, MIT Press, Cambridge, MA
> ISBN 0-262-69131-0

Articles about, and interviews with, 34 of the people to whom goes much of the credit for the computer world being the way it is, from Charles Babbage to Donald Knuth.

"The Computer Pioneers" by David Ritchie
1986, Simon & Schuster, New York
ISBN 0-671-52397-X

This one concentrates in the late 1930s and the 1940s, with one chapter for each of the key inventors or groups of that period. The author is a journalist and the book is very readable.

"The Computer -- My Life"
Original German version by Konrad Zuse:
“Der Computer -- mein Lebenswerk"
1993, Springer-Verlag, Berlin
ISBN 3-540-56292-3
English translation by Patricia McKenna and J. Andrew Ross
1993, Springer-Verlag, Berlin and New York
ISBN 0-387-56453-5 (New York), 3-540-56453-5 (Berlin).

An autobiography.

"Encyclopedia of Computer Science and Engineering", 2nd ed.
editor Anthony Ralston, associate Editor Edwin D. Reilly Jr.
1983, Van Nostrand Reinhold, New York
ISBN 0-442-24496-7

The title is self-explanatory.

"The Computer Comes of Age"
Original French version by R. Moreau:"Ainsi naquît l'informatique"
1981
English translation by J. Howlett
1984, MIT Press, Cambridge, MA
ISBN 0-262-36103-2

Concentrating on the period from the mid 1940s to mid 1960s, and with a noticeably IBMish viewpoint.

"ENIAC: The Triumphs and Tragedies of the World's First Computer"
by Scott McCartney
1999, Walker and Co., New York
ISBN 0-8027-1348-3

This book has somewhat a wider scope than the title suggests, covering events in the lives of Presper Eckert and John Mauchly over several decades. However, it is strictly centered on the two men and tends to "prove" their pioneering status by omitting any developments they weren't involved with.

Two articles from Scientific American were also sources. One in the August 1988 issue was about the Atanasoff-Berry machines, and one in the February 1993 issue of was about Babbage's difference engines and the modern-day completion of one of them.

Information about the cipher-breaking machines came primarily from two books:

> "Seizing the Enigma: the Race to Break the German U-Boat Codes, 1939-1943"
> by David Kahn
> 1991, Houghton Mifflin, Boston
> ISBN 0-395-42739-8
>
> "Codebreakers: The Inside Story of Bletchley Park"
> edited by F.H. Hinsley and Alan Stripp
> 1993, Oxford University Press, Oxford and New York
> ISBN 0-19-820327-6

Kahn is also the author of the monumental cryptological history "The Codebreakers"; this book is oriented more to a popular readership but still contains plenty of technical detail. The second book collects articles by various individuals involved with the cipher-breaking work; some are quite technical and others not.

A few items of information come from other sources, not listed individually here. One correction about Konrad Zuse came from his son Horst.

And finally, the book

> Faster than Thought editor B. V. Bowden
> 1953, Pitman, New York and London

provided an interesting early perspective, and the signature quote.

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I've tried to mention in this chronology each machine within the relevant time period that meets the following criteria. First, it must use a digital technique to do arithmetic or other logic. This eliminates, for instance, the slide rule and the differential analyzer, while allowing the cipher-breaking machines of the Second World War to be included.

Second, it must actually do the arithmetic or other work rather than just assisting the user's memory. I consider this to eliminate the abacus as well as, say, Napier's Bones.

Third, to count as being able to do an operation, the machine must do essentially the whole computation, with little or no assistance from the user. You could subtract 16 on a 6-digit Pascaline by adding 999,984, but this doesn't mean we should say that a Pascaline could subtract.

Fourth, it must work on user-supplied operands. In 1364, Giovanni de Dondi completed a clock where chains of various lengths, advancing in discrete annual steps to represent calendar cycles, computed the date of Easter; but this still does not qualify. (For details of this clock see "Some Outstanding Clocks over Seven Hundred Years, 1250-1950" by H. Alan Lloyd, 1958, Leonard Hill.)

And finally, the machine must have either been technologically innovative, or else well known and influential. For certain concepts of special importance, I have also listed the first time they were *described*, although they were not implemented at that time.

Where I do not describe the size of a machine, it is generally suitable for desktop use if it has no memory and is unprogrammable or if it is a small prototype, but would about fill a small room if it has memory or significant programmability.

The term "full-scale" is used, in contrast to "prototype", to refer to a machine with sufficient capacity to do regular useful work. For the sorts of machines described toward the end of the chronology, I generally consider them "completed" when they first run a program, even though they may be subject to further modifications and debugging. Unfortunately, sources referring to the "completion" of a machine are not always clear as to exactly what they mean by it.

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1623. Wilhelm Schickard (1592-1635), of Tübingen, Württemberg (now in Germany), makes his "Calculating Clock". This is a 6-digit machine that can add and subtract, and indicates overflow by ringing a bell. Mounted on the machine is a set of Napier's Rods (or Bones), a memory aid facilitating multiplications. The machine and plans are lost and forgotten in the war that is going on.

The plans will finally be rediscovered in 1935, only to be lost in war again, and then re-rediscovered in 1956 by the same man! The machine will be reconstructed in 1960, and found to be workable.

(Schickard is a friend of the astronomer Kepler.)

(According to an informal communication, Schickard sometimes uses the device for 7-digit calculations, counting rings of the overflow bell by putting rings on one of his, uh, personal digits...)

1644-5. Blaise Pascal (1623-62), of Paris, makes his "Pascaline". This 5-digit machine uses a different carry mechanism from Schickard's, with rising and falling weights instead of a direct gear drive; it can be extended better to support more digits, but it cannot subtract, and probably is less reliable than Schickard's simpler method.

Where Schickard's machine is forgotten -- and indeed Pascal is apparently unaware it ever existed -- Pascal's becomes well known and establishes the computing machine concept in the intellectual community. He makes more machines and sells about 10-15 of them, some supporting as many as 8 digits. (Several survive to the present day.) Patents being a thing of the future, others also sell copies of Pascal's machine.

(Pascal is also the inventor of the bus.)

c.1668. Sir Samuel Morland (1625-95), of England, produces a non-decimal adding machine, suitable for use with English money. Instead of a carry mechanism, it registers carries on auxiliary dials, from which the user must reenter them as addends.

1674. Gottfried Wilhelm von Leibniz (1646-1716), of Leipzig, designs his "Stepped Reckoner", which is constructed by a man named Olivier, of Paris. It uses a movable carriage so that it can multiply, with operands of up to 5 and 12 digits and a product of up to 16. The user has to turn a crank once for each unit in each digit in the multiplier; a fluted drum translates the turns into additions. But the carry mechanism requires user intervention, and doesn't really work in all cases anyway.

Leibniz's machine doesn't get forgotten, but it does get misplaced in an attic within a few years -- and will stay there until 1879 when it will be noticed by a man working on the leaky roof!

(Leibniz, or Leibnitz, is also the co-inventor of calculus.)

1775. Charles, the third Earl Stanhope, of England, makes a successful multiplying calculator similar to Leibniz's.

1770-6. Mathieus Hahn, somewhere in what will be Germany, also makes a successful multiplying calculator.

1786. J. H. Müller, of the Hessian army, conceives the idea of what came to be called a "difference engine". That's a special-purpose calculator for tabulating values of a polynomial, given the differences between certain values so that the polynomial is uniquely specified; it's useful for any function that can be approximated by a polynomial over suitable intervals. Müller's attempt to raise funds fails and the project is forgotten.

1820. Charles Xavier Thomas de Colmar (1785-1870), of France, makes his "Arithmometer", the first mass-produced calculator. It does multiplication using the same general approach as Leibniz's calculator; with assistance from the user it can also do division. It is also the most reliable calculator yet. Machines of this general design, large enough to occupy most of a desktop, continue to be sold for about 90 years.

1822. Charles Babbage (1792-1871), of London, having reinvented the difference engine, begins his (government-funded) project to build one by constructing a 6-digit calculator using gear technology similar to that planned for the difference engine.

1832. Babbage and Joseph Clement produce a prototype segment of his difference engine, which operates on 6-digit numbers and 2nd-order differences (i.e. can tabulate quadratic polynomials).

The complete engine, which would be room-sized, is planned to be able to operate both on 6th-order differences with numbers of about 20 digits, and on 3rd-order differences with numbers of 30 digits. Each addition would be done in two phases, the second one taking care of any carries generated in the first. The output digits would be punched into a soft metal plate, from which a plate for a printing press could be made.

But there are various difficulties, and no more than this prototype piece is ever assembled.

1834. George Scheutz, of Stockholm, produces a small difference engine in wood, after reading a brief description of Babbage's project.

1834. Babbage conceives, and begins to design, his "Analytical Engine". Whether or not this machine, if built, would constitute a computer depends on exactly how "computer" is being defined. One essential feature of present-day computers is absent from the design: the "stored-program" concept, which is necessary for implementing a compiler. The program would have been in read-only memory, specifically in the form of punch cards. (In this chronology, such machines will be called "programmable calculators".)

Babbage continues to work on the design for years, though after about 1840 the changes are minor. The machine would operate on 40-digit numbers; the "mill" (CPU) would have 2 main accumulators and some auxiliary ones for specific purposes, while the "store" (memory) would hold perhaps 100 more numbers. There would be several punch card readers, for both programs and data; the cards would be chained and the motion of each chain could be reversed. The machine would be able to perform conditional jumps. There would also be a form of microcoding: the meaning of instructions would depend on the positioning of metal studs in a slotted barrel, called the "control barrel".

The machine would do an addition in 3 seconds and a multiplication or division in 2-4 minutes.

1842. Babbage's difference engine project is officially canceled. (The cost overruns have been considerable, and Babbage is spending too much time on redesigning the Analytical Engine.)

1843. Scheutz and his son Edvard Scheutz produce a 3rd-order difference engine with printer, and the Swedish government agrees to fund their next development.

1847-9. Babbage designs an improved, simpler difference engine, which will operate on 7th-order differences and 31-digit numbers, but nobody is interested in paying to have it built.

(In 1989-91, however, a team at London's Science Museum will do just that. They will use components of modern construction, but with tolerances no better than Clement could have provided... and, after a bit of tinkering and detail-debugging, they will find that the machine does indeed work.)

1853. To Babbage's delight, the Scheutzes complete the first full-scale difference engine, which they call a Tabulating Machine. It operates on 15-digit numbers and 4th-order differences, and produces printed output as Babbage's would have. A second machine is later built to the same design by the firm of Bryan Donkin of London.

1858. The first Tabulating Machine is bought by the Dudley Observatory in Albany, New York, and the second one by the British government. The Albany machine is used to produce a set of astronomical tables; but the observatory's director is then fired for this extravagant purchase, and the machine is never seriously used again, eventually ending up in a museum. (The second machine, however, will have a long and useful life.)

1871. Babbage produces a prototype section of the Analytical Engine's mill and printer.

1878. Ramon Verea, living in New York City, invents a calculator with an internal multiplication table; this is much faster than the shifting carriage or other digital methods. He isn't interested in putting it into production; he just wants to show that a Spaniard can invent as well as an American.

1879. A committee investigates the feasibility of completing the Analytical Engine and concludes that it is impossible now that Babbage is dead. The project is then largely forgotten and is unknown to most of the people mentioned in the last part of this chronology -- though Howard Aiken is an exception.

1885. A multiplying calculator more compact than the Arithmometer enters mass production. The design is the independent, and more or less simultaneous, invention of Frank S. Baldwin, of the United States, and T. Odhner, a Swede living in Russia. The fluted drums are replaced by a "variable-toothed gear" design: a disk with radial pegs that can be made to protrude or retract from it.

1886. Dorr E. Felt (1862-1930), of Chicago, makes his "Comptometer". This is the first calculator where the operands are entered merely by pressing keys rather than having to be, for example, dialed in. It is feasible because of Felt's invention of a carry mechanism fast enough to act while the keys return from being pressed.

1889. Felt invents the first printing desk calculator.

1890. US Census results are tabulated for the first time with significant mechanical aid: the punch card tabulators of Herman Hollerith (1860-1929) of MIT, Cambridge, MA. This is the start of the punch card industry. The cost of the census tabulation is 98% *higher* than the previous one, in part because of the temptation to use the machines to the fullest and tabulate more data than formerly possible, but the tabulation is completed in a much shorter time. Another precedent is that the cards are read electrically.

(Contrary to popular impression and to earlier versions of this chronology, Hollerith's cards of 1890 are not the same size as US paper money of the time; they are much smaller. Other sizes of punch cards will also appear within a few years.)

1892. William S. Burroughs (1857-98), of St. Louis, invents a machine similar to Felt's but more robust, and this is the one that really starts the office calculator industry.

(This machine is still hand powered, but it won't be many years before electric calculators appear.)

1906. Henry Babbage, Charles's son, with the help of the firm of R. W. Munro, completes the mill of his father's Analytical Engine, just to show that it would have worked. It does. The complete machine is never produced.

1919. W. H. Eccles and F. W. Jordan publish the first flip-flop circuit design.

c.1920. Eugène Carissan of France constructs a machine for factoring whole numbers, based on 14 rotating metal rings studded with pegs.

1926. Derrick Henry Lehmer, at Berkeley, CA, constructs a machine for factoring whole numbers, based on 19 bicycle chains. A later machine will use punched tape -- not paper tape, but film stock.

(Lehmer is the son of mathmatician Derrick Norman Lehmer.)

1931-2. E. Wynn-Williams, at Cambridge, England, uses thyratron tubes to construct a binary digital counter for use in connection with physics experiments.

1932. Lehmer adds an optical reader to his punched-film factoring machine. It is now capable of 5,000 operations per second.

1935. International Business Machines introduces the "IBM 601", a punch card machine with an arithmetic unit based on relays and capable of doing a multiplication in 1 second. The machine becomes important both in scientific and commercial computation, and about 1,500 of them are eventually made.

Jun 1937. Konrad Zuse (1910-95) of Berlin writes in his diary a synopsis of the stored-program concept: "Die Operationen folgen einem Plan ähnlich einem Rechenplan. Mit Ausgangsbedingungen und Resultat. Dementsprechend Speicherplan. Jedoch kann der Speicher- oder Arbeitsplan sich aus den vorhergehenden Operationen ergeben (z.B. die Nummern der Speicherzellen) und sich so aus sich selbst aufbauen (vgl. 'Keimzelle')." That is, "The operations follow a plan similar to a computing plan. With initial conditions and result. Accordingly, a storage plan. However, the storage or work plan can still result from the preceding operations (e.g. the numbers in the storage cells) and in this way be built from itself (cf. 'germ cell')."

Nov 1937. George Stibitz (c.1904 - 1995) of the Bell Telephone Laboratories (Bell Labs), New York City, constructs on his kitchen table the "K-Model": a demonstration 1-bit binary adder using relays.

1937. Alan M. Turing (1912-54), of Cambridge University, England, publishes a paper on "computable numbers". This paper solves a mathematical problem, but the solution is achieved by reasoning (as a mathematical device) about the theoretical simplified computer known today as a Turing machine.

Nov 1938. Marian Rejewsky (a man, 1905-80) and his group, working for Poland's Biuro Szyfrów (Cipher Office), complete the first "bomba", a machine using electromechanical digital logic for trying out combinations of letters to solve the Germans' Enigma cipher. The Enigma machine uses a series of disks ("rotors") with sets of 26 contacts wired so as to permute and repermute the alphabet; the sequence of rotors and their initial settings are changed from time to time, forming a key.

The bomba contains its own set of rotors like the Enigma's, and its function is to determine, through a combination of logic with an exhaustive search of rotor positions, whether a particular short piece of guessed plaintext and a particular piece of encrypted text could correspond. If the plaintext was correctly guessed, then the key can be derived from the bomba results, and not only the rest of that message, but all others using the same key can then be decrypted. And if it wasn't, then the same guess will be tried against other messages.

(But the next month, the Germans will add a selection of additional rotors to their Enigma machines. The Poles, not having the resources to build more bomby, in July 1939 will turn over all their discoveries to the British and the French.)

1938. Claude E. Shannon (1916-2001) publishes a paper on the implementation of symbolic logic using relays.

1938. Helmut Schreyer, of Berlin, designs logic circuitry based on a combination of vacuum tubes and neon lamps. (By 1940 he will have produced a 10-bit adder and a prototype memory unit.)

1938. Zuse, with some assistance from Schreyer, completes a prototype electromechanical binary programmable calculator, called the "V1" at the time but retroactively renamed "Z1" after the war. It works with floating point numbers having a 7-bit exponent, 16-bit mantissa, and a sign bit. The memory uses sliding metal parts to store 16 such numbers, and works well; but the arithmetic unit, using secondhand relays and stepping switches, is less successful.

The program is read from punched tape. Like Lehmer, Zuse uses film rather than paper for his tape; specifically, discarded 35 mm movie film. Data values can be entered from a numeric keyboard, and outputs are displayed on electric lamps.

Nov 1939. John V. Atanasoff (1903-95) and graduate student Clifford Berry (1918-63), of Iowa State College (now the Iowa State University), Ames, Iowa, complete a prototype 25-bit adder. This is the first machine to calculate using vacuum tubes. To store the operands, it has 2 25-bit words of memory in the form of capacitors (with refresh circuits using more vacuum tubes -- the first regenerative memory) mounted one word on each side of a revolving disk. There is no input device; the user enters the operands directly into memory, by tapping the appropriate capacitors with a wire!

Nov 1939. At Bell Labs, Samuel Williams and Stibitz complete a calculator which can operate on complex numbers, and give it the imaginative name of the "Complex Number Calculator"; it is later known as the "Model I Relay Calculator". It uses telephone switching parts for logic: 450 relays and 10 crossbar switches. Numbers are represented in "plus 3 BCD"; that is, for each decimal digit, 0 is represented by binary 0011, 1 by 0100, and so on up to 1100 for 9; this scheme requires fewer relays than straight BCD.

Rather than requiring users to come to the machine to use it, the calculator is provided with three remote keyboards, at various places in the building, in the form of teletypes. Only one can be used at a time, and the output is automatically displayed on the same one.

1939. Zuse and Schreyer begin work on the "V2" (later "Z2"), which will marry the Z1's existing mechanical memory unit to a new arithmetic unit using relay logic. The project is interrupted for a year when Zuse is drafted.

Early 1940. Turing and Gordon Welchman (1906-85), working for the British government codebreaking department deceptively named the Government Code and Cypher School, at Bletchley Park, Bletchley, England, successively improve the design of the bomba by adding further logic circuits. These greatly reduce the number of false solutions. With quantity production of these machines, now called bombes, the full-scale breaking of Enigma ciphers becomes a practical proposition.

(After the US joins the war, they will make and use them too. Improvements on the machines will continue, as the Germans also improve the cipher.)

1940. Zuse is released from the army and completes the Z2. It works better than the Z1, but isn't reliable enough. (Later he is drafted again, and released again.)

Sep 1940. Stibitz, attending a mathematical conference in Hanover, NH, to present a paper on the Complex Number Calculator, demonstrates operation of the machine from a remote location by teletype connection.

Summer 1941. Atanasoff and Berry complete a special-purpose calculator for solving systems of simultaneous linear equations, later called the "ABC" ("Atanasoff-Berry Computer"). This uses the same regenerative capacitor memory as their prototype, but with 60 50-bit words of it, mounted on two revolving drums. The clock speed is 60 Hz, and an addition takes 1 second. (For the purposes of this calculator, multiplication is not required.) There are circuits to convert between binary and decimal for input and output; the machine includes several hundred vacuum tubes altogether.

For secondary memory the ABC uses punch cards, moved around by the user. The holes are not actually punched in the cards, but burned by an electric spark. The card system is a partial failure; its error rate of 0.001% is too high to solve large systems of equations.

(Atanasoff will leave Iowa State after the US enters the war, and this will end his work on digital computing machines. The ABC will largely forgotten within a few years, and dismantled in 1946 when the storage space is needed.)

Dec 1941. Now working with limited backing from the DVL (German Aeronautical Research Institute), Zuse completes the "V3" (later "Z3"): the first operational programmable calculator. It works with floating point numbers having a 7-bit exponent, 14-bit mantissa (with a "1" bit automatically prefixed unless the number is 0), and a sign bit. The memory uses relays; with a capacity of 64 words, it needs over 1,400 of them. There are 1,200 more relays in the arithmetic and control units. The machine is the size of a closet.

The program, input, and output are implemented as described above for the Z1. Conditional jumps are not available. The machine can do 3-4 additions per second, and takes 3-5 seconds for a multiplication. Zuse considers the machine a prototype; it doesn't have enough memory to be much use for the equation-solving problems that the DVL was mostly interested in.

(In 1943, an air raid will destroy Zuse's workshop, and the Z3 with it, as well as his home nearby. A replica Z3 will be built in 1960 for the Deutsches Museum in Munich. And in 1967, the Patent Office of West Germany will finally rule on Zuse's 1941 application for a patent on the Z3, rejecting it "mangels Erfindungshöhe": "for an insufficient degree of invention"!)

1942. Zuse completes the S1, the first digital machine for process control. Attached sensors measure the profile of the wing of a flying bomb under construction; the readings are converted to digital and computations are run to determine how much the wing deviates from the ideal shape and needs to be adjusted. (This is cheaper than making it accurately in the first place.) The machine contains 800 relays; the program is literally wired in, each instruction being read by advancing a set of stepping switches.

Jan 1943. Howard H. Aiken (1900-73) and his IBM-backed team at Harvard University, Cambridge, MA, complete the "ASCC Mark I" ("Automatic Sequence-Controlled Calculator Mark I"), also called the "Harvard Mark I". This electromechanical machine is the first programmable calculator to be widely known: Aiken is to Zuse as Pascal to Schickard.

The machine is 51 feet long, weighs 5 tons, and incorporates 750,000 parts. It includes 72 accumulators, each incorporating its own arithmetic unit as well as a mechanical register with a capacity of 23 digits plus sign. (See the ENIAC entry, below, for a more detailed description of such an architecture.) The arithmetic is fixed-point, with a plugboard setting determining the number of decimal places. I/O facilities include card readers, a card punch, paper tape readers, and typewriters. There are 60 sets of rotary switches, each of which can be used as a constant register -- sort of a mechanical read-only memory. An addition takes 1/3 second, and a multiplication, 1 second.

The program is read from one paper tape; data can be read from the other tapes, or the card readers, or from the constant registers.

Conditional jumps are not available. However, in later years the machine is modified to support multiple paper tape readers for the program, with the transfer from one to another being conditional, sort of like a conditional subroutine call. Another addition allows the provision of plugboard-wired subroutines callable from the tape.

Apr 1943. Max Newman, Wynn-Williams, and their team at Bletchley Park, complete the "Heath Robinson". This is a prototype machine for breaking the new German ciphers collectively codenamed the "Fish" ciphers, which are based on bit-level manipulations rather than permutations of the alphabet. The machine uses a combination of electronics and relay logic. It reads data optically at 2,000 characters per second from 2 closed loops of paper tape, each typically about 1,000 characters long.

(Newman had taught Turing at Cambridge, and had been the first person to see a draft of Turing's 1937 paper. Heath Robinson is the name of a British cartoonist known for drawings of comical machines, like the American Rube Goldberg. Two later machines in the series will be named for London stores with "Robinson" in their names!)

Apr 1943. John W. Mauchly (pronounced Mawkly; 1907-80), J. Presper Eckert (1919-95), and John Brainerd at the Moore School of Electrical Engineering, of the University of Pennsylvania, Philadelphia, write a "Report on an Electronic Diff. Analyzer" for the US Army's Ballistics Research Lab. The abbreviation "Diff." Is intended to reflect the fact that the proposed machine, eventually named the ENIAC ("Electronic Numerator, Integrator, Analyzer, and Computer"; some sources omit "Analyzer" or have "Calculator" as the last word), is to use *differences* to compute digitally the same results that a *differential* analyzer would compute by analog means. The BRL, which has a great interest in calculating shell trajectories to produce gun aiming tables, accepts the proposal and work on the ENIAC begins in secret.

Sep 1943. Williams and Stibitz complete the "Relay Interpolator", later called the "Model II Relay Calculator". This is a programmable calculator; again, the program and data are read from paper tapes. An innovative feature is that, for greater reliability, numbers are represented in a biquinary format using 7 relays for each digit, of which exactly 2 should be "on": 01 00001 for 0, 01 00010 for 1, and so on up to 10 10000 for 9.

(Some of the later machines in this series will use the biquinary notation for the digits of floating-point numbers.)

Dec 1943. Tommy Flowers (1905-98) and his team at Bletchley Park complete the first "Colossus". This full-scale successor to the "Robinson" series machines is entirely electronic, incorporating 2,400 vacuum tubes for logic. It has 5 paper tape loop readers, each working at 5,000 characters per second.

(10 Colossi will eventually be built, then destroyed after the war to maintain secrecy. Turing also has an important role at Bletchley Park, but

does not work directly on the machines. In the 1990s Bletchley Park will become a museum, and in 1996 a replica Colossus will be completed there.)

1944-5. Zuse almost completes his first full-scale machine, the "V4" (later "Z4"), which resembles his earlier designs. Its memory reverts to the Z1's mechanical design, storing 1,000 words of 32 bits in less then a cubic meter; the equivalent in relays would have filled a large room.

As the war begins to go very badly for Germany, Zuse's work suffers major disruptions. The Z4 is moved three times within Berlin, then to Göttingen, and finally to the Bavarian village of Hinterstein where it is hidden. Here it survives the war, but the Allies don't understand what it is, and nobody in Germany is in a position to pay Zuse for more work.

1945. Zuse invents a programming language called Plankalkül.

Jun 1945. John von Neumann (1903-57), having joined the ENIAC team, drafts a report describing the future computer eventually built as the "EDVAC" ("Electronic Discrete Variable Automatic Computer" (!)); this is the first detailed description of the design of a stored-program computer, and gives rise to the term "von Neumann computer".

The first draft of the report fails to credit other team members such as Eckert and Mauchly; when this version becomes widely circulated, von Neumann gets somewhat too much credit for the design. The final version corrects the oversight, but too late.

(Von Neumann, also noted for his mental calculating ability, is the only one of the principal computer pioneers in the US familiar with Turing's 1937 paper.)

Nov 1945. Mauchly and Eckert and their team at the Moore School complete the ENIAC. It's too late for the war, and the total cost of $486,800 far exceeds the original budget of $150,000 (problems that Eckert and Mauchly will face again on later projects), but it works.

The ENIAC's architecture resembles that of the Harvard Mark I, but its components are entirely electronic, incorporating 17,468 vacuum tubes and more than 80,000 other components. The machine weighs 30 tons, covers about 1,000 square feet of floor, and consumes somewhere between 130 and 174 kilowatts of electricity (sources differ). Many of the modules are made to plug into the mainframe, to shorten the repair time when a tube or other component fails. The cost and downtime are further reduced by using circuits designed to work even if the components are off-specification, and wire of the type least preferred by hungry mice in experiments.

The machine incorporates 20 accumulators (the original plan was for 4). The accumulators and other units are all connected by several data buses, and a set of "program lines" for synchronization.  Each accumulator stores a 10-digit number, using 10 bits to represent each digit, plus a sign bit, and also incorporates circuits to add a number from a bus ("digit trunk") to the stored number, and to transmit the stored number or its complement to a bus.

A separate unit can perform multiplication (in about 3 milliseconds), while another does division and square roots; the inputs and outputs for both these units use the buses.  There are constant registers, as on the Harvard Mark I: 104 12-digit registers forming an array called the "function table".  100 of these registers are directly addressable by a 2-digit number from a bus (the others are used for interpolations). Finally, a card reader is available to input data values, and there is a card punch for output.

The program is set up on a plugboard -- this is considered reasonable since the same or similar program would generally be used for weeks at a time. For example, connecting certain sockets would cause accumulator 1 to transmit its contents onto data bus 1 when a pulse arrived on program line 1; meanwhile several accumulators could be adding the value from that data bus to their stored value, while others could be working independently. The program lines are pulsed under the control of a master unit, which can perform iterations.

The ENIAC's clock speed is 100 kHz.

Mauchly and Eckert apply for a patent.  The university disputes this at first, but they settle.  The patent is finally granted in 1964, but is overturned in 1973, in part because of the previous work by Atanasoff, whom Mauchly had visited in June 1941.

Feb 1946.  The ENIAC is revealed to the public.  A panel of lights is added to help show reporters how fast the machine is and what it is doing; and apparently Hollywood takes note.

Jul-Aug 1946. The Moore School gives a course on "Theory and Techniques for Design of Electronic Computers"; lectures are given by Eckert, Mauchly, Stibitz, von Neumann, and Aiken among others.  The course leads to several projects being started, among them the EDSAC.

Jul 1947.  Aiken and his team complete the "Harvard Mark II", a large programmable calculator using relays both for its 50 floating-point registers and for the arithmetic unit, 13,000 of them in all.

Sep 1947. A moth (?-1947) makes the mistake of flying into the Harvard Mark II. A whimsical technician makes the logbook entry "first actual case of bug being found", and annotates it by taping down the remains of the moth.

(The term "bug" was of course already in use; that's why it's funny. Grace Murray Hopper (1906-92), a programmer on the machine, will tell the story so many times in later years that people will come to think she found the moth herself.)

Oct 1947. Freddie C. Williams (1911-77) and Thomas Kilburn (1921-), working under Newman at Manchester University, complete a new type of digital memory (possibly from an original suggestion by Presper Eckert), which comes to be called the Williams tube or CRT memory. It uses the residual charges left on the screen of a CRT after the electron beam has been fired at it; the bits are read by firing another beam through them and reading the voltage at an electrode beyond the screen, then rewriting. The technique is a little unreliable, but is fast, and also relatively cheap because it can use existing CRT designs; and it is much more compact than any other memory existing at the time. A further advantage is that if the CRT face is exposed to view, the values in the memory are visible!

1947. Frederick Viehe (?-1960), of Los Angeles, applies for a patent on an invention which is to use magnetic core memory.

1947. Aiken predicts that the United States will need a total of six electronic digital computers.

c.1947. The magnetic drum memory is independently invented by several people, and the first examples are constructed.

(As noted below, some early machines will use drums as main memory rather than secondary memory.)

Jan 1948. Wallace Eckert (1902-71, no relation to Presper Eckert) of IBM, with his team, completes the "SSEC" ("Selective Sequence Electronic Calculator"). This technological hybrid has 8 vacuum tube registers, 150 words of relay memory, and 66 paper tape loops storing a total of 20,000 words. The word size is 20 digits, stored in BCD in the registers.

As with the Harvard Mark I in its later form, the machine can be switched to read instructions from any of the paper tapes. There is also some use of plugboards in its programming. But it can also cache some instructions in memory and read them from there; thus, in effect, it can operate either as a stored-program computer (with a very small program memory) or not.

Because it can do this, IBM's point of view is that this is the first computer.

Jun 1948. Williams, Kilburn, and their team complete a prototype computer. This is the first machine that everyone would call a computer, because it's the first with a true stored-program capability. At this point it has no formal name, though one paper calls it the "Small-Scale Experimental Machine"; later the machine will become known as the "Manchester Mark I", while its initial form at this date will be nicknamed the "Baby".

The machine's main memory of 32 32-bit words occupies a single Williams tube. (There are others on the machine, but less densely used: one contains only an accumulator.)

The machine's programs are initially entered in binary on a keyboard, and the output is read in binary from the face of another Williams tube. Later Turing joins the team (see also the "Pilot ACE", below) and devises a primitive form of assembly language, one of several developed at about the same time in different places.

(In the 1990s a replica of the Baby is to be constructed, with completion scheduled for the 50th anniversary year of 1998.)

Sep 1948. The ENIAC is improved, using ideas from Richard F. Clipper of the BRL and Nicholas Metropolis of Los Alamos. Each program line is permanently wired for a different operation, and a new converter unit allows them to be addressed by a program, the way the function table can -- thus implementing, in effect, opcodes. With this change, the program can now be entered via the *function table*.

(This conversion will sometimes be described as making the ENIAC into a stored-program computer, but the program memory is still read-only. However, setting up a program now takes a matter of hours, rather than days as before. The ENIAC will also acquire a magnetic core memory in 1952, but will survive only until 1955.)

Fall 1948. IBM introduces the "IBM 604", a programmable calculator and card punch using vacuum tubes. It can read a card, perform up to 60 arithmetic operations in 80 milliseconds, and punch the results on the same card. The programming is by plugboard.

All machines first mentioned in the chronology from here on are stored-program computers.

1949-51. Jay W. Forrester and his team at MIT construct the "Whirlwind" for the US Navy's Office of Research and Inventions. The vague date is because its advance to full-time operational status is gradual. Its original form has 3,300 tubes and 8,900 crystal diodes. It occupies 2,500 square feet of floor. Its 2,048 16-bit words of CRT memory use up $32,000 worth of tubes each month. There is also a graphical I/O device consisting of a CRT (only one dot can be displayed at a time) and a light pen. This allows the machine to be used for air traffic control.

The Whirlwind is the first computer designed for real-time work; it can do 500,000 additions or 50,000 multiplications per second.

Spring 1949. Forrester conceives the idea of magnetic core memory as it is to become commonly used, with a grid of wires used to address the cores. The first practical form, in 1952-53, will replace the Whirlwind's CRT memory and render obsolete all types of main memory then existing.

April 1949. The Manchester Mark I, no longer the Baby as its main memory has been upgraded to 128 40-bit words (on two CRTs), acquires a secondary memory in the form of a magnetic drum holding a further 1,024 words. Also at about this time, two index registers are added to the machine.

(The index register's contents are added, not to the address taken from an instruction, but to the entire instruction, thus potentially changing the opcode! Calling Mel...)

May 1949. Maurice Wilkes (1913-) and his team at Cambridge University complete the "EDSAC" ("Electronic Delay Storage Automatic Computer"), which is closely based on the EDVAC design report from von Neumann's group -- Wilkes had attended the 1946 Moore School course. The project is supported both financially and with technical personnel from J. Lyons & Co. Ltd., a large British firm in the food and restaurant business.

This is the first operational full-scale stored-program computer, and is therefore the final candidate for the title of "the first computer".

Its main memory is of a type that had existed for some years, but had not been used for a computing machine: the "ultrasonic delay line" memory. It had been invented originally by William Shockley of Bell Labs (also one of the co-inventors of the transistor, in 1948), and improved by Presper Eckert for use with radar systems. It works by repeatedly converting from the usual electrical data pulses to ultrasonic pulses directed along, typically, the length of a tank of mercury; on arrival at the other end, the pulses are converted back to electrical form. The memory must be maintained at a particular temperature, and only the few bits currently in electrical form are accessible. In the EDSAC, 16 tanks of mercury give a total of 256 35-bit words (or 512 17-bit words).

The clock speed of the EDSAC is 500 kHz; most instructions take about 1.5 ms to execute. Its I/O is by paper tape, and a set of constant registers is provided for booting.

The software eventually supports the concept of relocatable procedures with addresses bound at load time.

Aug 1949. Presper Eckert and Mauchly, having formed their own company, complete the "BINAC" ("Binary Automatic Computer") for the US Air Force. Designed as a first step to in-flight computers, this has dual (redundant) processors each with 700 tubes and 512 31-bit words of memory. Each processor occupies only 4 square feet of floor space and can do 3,500 additions or 1,000 multiplications per second.

The designers are thinking mostly of their forthcoming "UNIVAC" "Universal Automatic Computer") and don't spend much time making the BINAC as reliable as it should be, but the tandem processors compensate somewhat.

Sep 1949. Aiken's team completes the "Harvard Mark III". This computer has separate magnetic drum memories for data and instructions. Only some of the data drums can be addressed by the CPU; the others serve as secondary memory. The total memory capacity is 4,000 instructions, 350 16-bit words in the main data drums, and 4,000 words more in the secondary memory. The machine contains over 5,000 vacuum tubes and 2,000 relays, and can do about 80 multiplications per second.

May 1950. A group at the National Physical Laboratory, Teddington, England, complete the "Pilot ACE" (pilot project for an "Automatic Computing Engine"). This had been largely designed by Turing when he was there in 1945-47; he had left and gone to Manchester because the designs were not being implemented. The main memory of this computer is in the form of 200 separate ultrasonic delay lines, thus allowing better addressability than other ultrasonic-based machines. An additional group of short delay lines serve as registers, each of which performs a particular operation automatically on a number directed to it. Most operations then consist simply of routing a number, or a counted stream of numbers, from one delay line to another. Punch cards are used for input and output; a drum will be added later for secondary memory.

(A successor to this machine will be named "DEUCE".)

May 1950. A group at the US National Bureau of Standards, Washington, which had found itself unable to wait for commercial computers to appear, completes "SEAC" (Standards Eastern Automatic Computer"). The design was kept simple for the sake of rapid implementation. To keep the number of vacuum tubes down, 12,000 of the new germanium diodes are used. The ultrasonic delay line memory holds 512 45-bit words.

July 1950. SEAC's western counterpart "SWAC", in Los Angeles, is completed and becomes the fastest computer in the world. It has Williams tube memory, which has problems because the tubes' phosphor layers were contaminated by lint at the former mattress factory where the tubes were made, and only 256 37-bit words of main memory are operable. But it can do an addition in 64 microseconds, and a drum is added later to augment the memory.

1950. Zuse's Z4 is finally completed and goes into service at ETH (Federal Polytechnical Institute) in Zurich, Switzerland. The design is modified so that it can do conditional jumps. The machine also implements a form of instruction pipelining, with the program tape being read 2 instructions ahead and various optimizations performed automatically.

The Z4 remains in use for 5 years at ETH and 5 more in France, and Zuse soon begins making his machines commercially. He eventually sells some 300 machines before being bought out by Siemens.

1950. Douglas Hartree (the leading expert in the country on the specialized computing machines called differential analyzers) gives his professional opinion to Ferranti Ltd., of Manchester: as the 3 existing computer projects will suffice to handle all the calculations that will ever be needed in England, Ferranti would be well advised to drop the idea of making computers for commercial sale.

Feb 1951. A rather more optimistic Ferranti Ltd. completes the first commercial computer. This is yet another "Mark I", but is also known as the "Manchester Mark II", "MUDC", "MUEDC", and "MADAM"! It has 256 40-bit words of main memory and 16K words of drum, and includes 8 index registers (they work the same way as on the Manchester Mark I, which this machine was derived from). An eventual total of 8 of these machines are sold.

Mar 1951. Presper Eckert and Mauchly, having sold their company to Remington Rand, complete the first "UNIVAC", which is the first US commercial computer. (The US census department is the first customer.) It has 1,000 12-digit words of ultrasonic delay line memory and can do 8,333 additions or 555 multiplications per second; it contains 5,000 tubes and covers 200 square feet of floor. For secondary memory it uses 1/2 inch magnetic tapes of nickel-coated bronze, which store 128 characters per inch; 10,000 characters can be read per second.

Fall 1951. The Lyons company receives its reward for supporting the EDSAC, as T. Raymond Thompson, John Simmons, and their team complete the "LEO I" ("Lyons Electronic Office I"), which is modeled closely after the EDSAC.

Its ultrasonic memory is 4 times as large, and avoids the usual temperature dependency by using one delay line as a master and synchronizing the others to it instead of to a clock.

The Lyons company wants the LEO I for its own use -- payroll, inventory, and so on; it is the first computer used for commercial calculations. But other companies now turn out to be interested in the LEO, and Lyons will soon find itself in the computer manufacturing business as well.

1951. Grace Murray Hopper, now of Remington Rand, invents the modern concept of the compiler.

1952. The EDVAC is finally completed. It has 4,000 tubes, 10,000 crystal diodes, and 1,024 44-bit words of ultrasonic memory. Its clock speed is 1 MHz.

1952. The IBM "Defense Calculator", later renamed the "701", the first IBM computer unless you count the SSEC, enters production at Poughkeepsie, New York. (The first one is delivered in March 1953; 19 are sold altogether. The machine is available with 2,048 or 4,096 36-bit words of CRT memory; it does 2,200 multiplications per second.)

(IBM stayed out of the computer market for some time because its president, Thomas Watson Sr., didn't want the company competing against its own business machines. His son and eventual successor, Thomas Jr., disagreed, and realized that if it was the US *military* that wanted to buy a computer, Thomas Sr. would not say no to them.)

1952. Grace Murray Hopper implements the first compiler, the "A-0". (But as with "first computer", this is a somewhat arbitrary designation.)

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A few things have happened since then, too, but this margin is too narrow...