





*Main article: **Calculator***

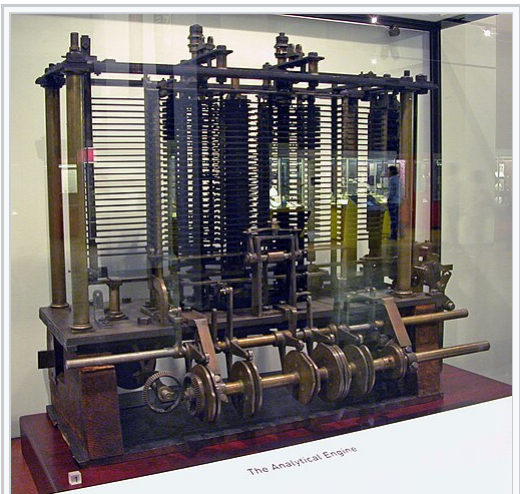
By the 20th century, earlier mechanical calculators, cash registers, accounting machines, and so on were redesigned to use electric motors, with gear position as the representation for the state of a variable. The word "computer" was a job title assigned to primarily women who used these calculators to perform mathematical calculations.<sup>[36]</sup> By the 1920s, British scientist **Lewis Fry Richardson**'s interest in weather prediction led him to propose **human computers** and **numerical analysis** to model the weather; to this day, the most powerful computers on **Earth** are needed to adequately model its weather using the **Navier–Stokes equations**.<sup>[37]</sup>

Companies like **Friden**, **Marchant Calculator** and **Monroe** made desktop mechanical calculators from the 1930s that could add, subtract, multiply and divide.<sup>[38]</sup> In 1948, the **Curta** was introduced by Austrian inventor **Curt Herzstark**. It was a small, hand-cranked mechanical calculator and as such, a descendant of **Gottfried Leibniz**'s **Stepped Reckoner** and **Thomas' Arithmometer**.

The world's first *all-electronic desktop* calculator was the British **Bell Punch ANITA**, released in 1961.<sup>[39][40]</sup> It used **vacuum tubes**, cold-cathode tubes and **Dekatrons** in its circuits, with 12 cold-cathode "**Nixie**" tubes for its display. The **ANITA** sold well since it was the only electronic desktop calculator available, and was silent and quick. The tube technology was superseded in June 1963 by the U.S. manufactured **Friden** EC-130, which had an all-transistor design, a stack of four 13-digit numbers displayed on a 5-inch (13 cm) **CRT**, and introduced **reverse Polish notation** (RPN).

## First proposed general-purpose computing device  [ edit ]

*Main article: **Analytical Engine***



Trial model of a part of the Analytical Engine, built by Babbage, as displayed at the Science Museum, London

The **Industrial Revolution** (late 18th to early 19th century) had a significant impact on the evolution of computing hardware, as the era's rapid advancements in machinery and manufacturing laid the groundwork for mechanized and automated computing. Industrial needs for precise, large-scale calculations—especially in fields such as navigation, engineering, and finance—prompted innovations in both design and function, setting the stage for devices like **Charles Babbage's difference engine** (1822).<sup>[41][42]</sup> This mechanical device was intended to automate the calculation of polynomial functions and represented one of the earliest applications of computational logic.<sup>[43]</sup>

Babbage, often regarded as the "father of the computer," envisioned a fully mechanical system of gears and wheels, powered by steam, capable of handling complex calculations that previously required intensive manual labor.<sup>[44]</sup> His difference engine, designed to aid navigational calculations, ultimately led him to conceive the **analytical engine** in 1833.<sup>[45]</sup> This concept, far more advanced than his difference engine, included an **arithmetic logic unit**, control flow through conditional branching and loops, and integrated memory.<sup>[46]</sup> Babbage's plans made his analytical engine the first general-purpose design that could be described as **Turing-complete** in modern terms.<sup>[47][48]</sup>

The analytical engine was programmed using **punched cards**, a method adapted from the **Jacquard loom** invented by **Joseph Marie Jacquard** in 1804, which controlled textile patterns with a sequence of punched cards.<sup>[49]</sup> These cards became foundational in later computing systems as well.<sup>[50]</sup> Babbage's machine would have featured multiple output devices, including a printer, a curve plotter, and even a bell, demonstrating his ambition for versatile computational applications beyond simple arithmetic.<sup>[51]</sup>

**Ada Lovelace** expanded on Babbage's vision by conceptualizing algorithms that could be executed by his machine.<sup>[52]</sup> Her notes on the analytical engine, written in the 1840s, are now recognized as the earliest examples of computer programming.<sup>[53]</sup> Lovelace saw potential in computers to go beyond numerical calculations, predicting that they might one day generate complex musical compositions or perform tasks like language processing.<sup>[54]</sup>

Though Babbage's designs were never fully realized due to technical and financial challenges, they influenced a range of subsequent developments in computing hardware. Notably, in the 1890s, **Herman Hollerith** adapted the idea of punched cards for automated data processing, which was utilized in the U.S. Census and sped up data tabulation significantly, bridging industrial machinery with data processing.<sup>[55]</sup>

The Industrial Revolution's advancements in mechanical systems demonstrated the potential for machines to conduct complex calculations, influencing engineers like **Leonardo Torres Quevedo** and **Vannevar Bush** in the early 20th century. Torres Quevedo designed an electromechanical machine with floating-point arithmetic,<sup>[56]</sup> while Bush's later work explored electronic digital computing.<sup>[57]</sup> By the mid-20th century, these innovations paved the way for the first fully electronic computers.<sup>[58]</sup>

## Analog computers  [ edit ]

*Main article: **Analog computer***

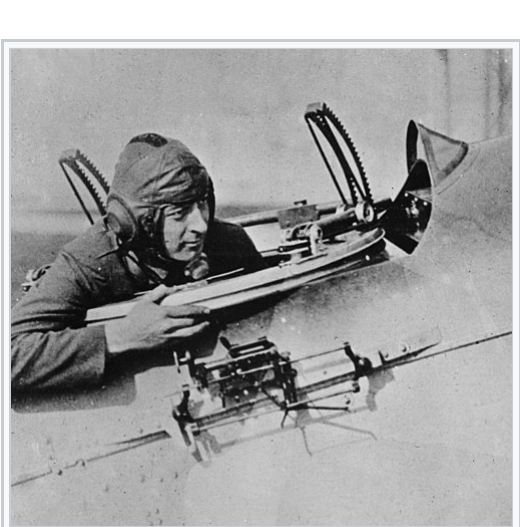
*Further information: **Mechanical computer***

In the first half of the 20th century, **analog computers** were considered by many to be the future of computing. These devices used the continuously changeable aspects of physical phenomena such as **electrical**, **mechanical**, or **hydraulic** quantities to **model** the problem being solved, in contrast to **digital computers** that represented varying quantities symbolically, as their numerical values change. As an analog computer does not use discrete values, but rather continuous values, processes cannot be reliably repeated with exact equivalence, as they can with **Turing machines**.<sup>[59]</sup>

The first modern analog computer was a **tide-predicting machine**, invented by **Sir William Thomson**, later Lord Kelvin, in 1872. It used a system of pulleys and wires to automatically calculate predicted tide levels for a set period at a particular location and was of great utility to navigation in shallow waters. His device was the foundation for further developments in analog computing.<sup>[60]</sup>

The **differential analyser**, a mechanical analog computer designed to solve differential equations by integration using wheel-and-disc mechanisms, was conceptualized in 1876 by **James Thomson**, the brother of the more famous Lord Kelvin. He explored the possible construction of such calculators, but was stymied by the limited output torque of the **ball-and-disk integrators**.<sup>[61]</sup> In a differential analyzer, the output of one integrator drove the input of the next integrator, or a graphing output.

A notable series of analog calculating machines were developed by **Leonardo Torres Quevedo** since 1895, including one that was able to compute the roots of arbitrary **polynomials** of order eight, including the complex ones, with a precision down to thousandths.<sup>[62][63][64]</sup>



A Mk. I Drift Sight. The lever just in front of the bomb aimer's fingertips sets the altitude, the wheels near his knuckles set the wind and airspeed.

An important advance in analog computing was the development of the first **fire-control systems** for long range **ship gunlaying**. When gunnery ranges increased dramatically in the late 19th century it was no longer a simple matter of calculating the proper aim point, given the flight times of the shells. Various spotters on board the ship would relay distance measures and observations to a central plotting station. There the fire direction teams fed in the location, speed and direction of the ship and its target, as well as various adjustments for **Coriolis effect**, weather effects on the air, and other adjustments; the computer would then output a firing solution, which would be fed to the turrets for laying. In 1912, British engineer **Arthur Pollen** developed the first electrically powered mechanical **analogue computer** (called at the time the Argo Clock).<sup>[*citation needed*]</sup> It was used by the **Imperial Russian Navy** in **World War I**.<sup>[*citation needed*]</sup> The alternative **Dreyer Table** fire control system was fitted to British capital ships by mid-1916.

Mechanical devices were also used to aid the **accuracy of aerial bombing**. **Drift Sight** was the first such aid, developed by **Harry Wimperis** in 1916 for the **Royal Naval Air Service**; it measured the **wind speed** from the air, and used that measurement to calculate the wind's effects on the trajectory of the bombs. The system was later improved with the **Course Setting Bomb Sight**, and reached a climax with **World War II** bomb sights, **Mark XIV bomb sight** (**RAF Bomber Command**) and the **Norden**<sup>[65]</sup> (**United States Army Air Forces**).

The art of mechanical analog computing reached its zenith with the **differential analyzer**,<sup>[66]</sup> built by H. L. Hazen and **Vannevar Bush** at **MIT** starting in 1927, which built on the mechanical integrators of **James Thomson** and the **torque amplifiers** invented by H. W. Nieman. A dozen of these devices were built before their

obsolescence became obvious; the most powerful was constructed at the **University of Pennsylvania's Moore School of Electrical Engineering**, where the **ENIAC** was built.

A fully electronic analog computer was built by **Helmut Hölzer** in 1942 at **Peenemünde Army Research Center**.<sup>[67][68][69]</sup>

By the 1950s the success of digital electronic computers had spelled the end for most analog computing machines, but **hybrid analog computers**, controlled by digital electronics, remained in substantial use into the 1950s and 1960s, and later in some specialized applications.

## Advent of the digital computer  [ edit ]

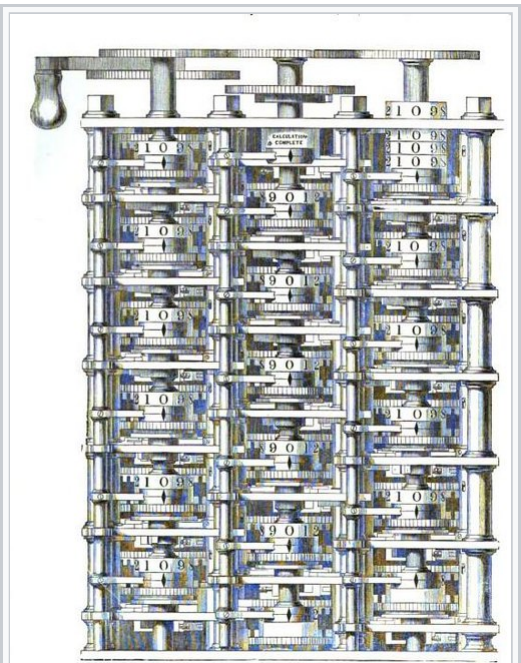
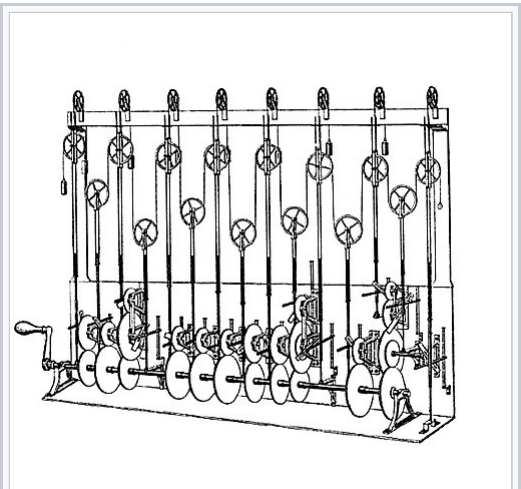
The principle of the modern computer was first described by computer scientist **Alan Turing**, who set out the idea in his seminal 1936 paper,<sup>[70]</sup> *On Computable Numbers*. Turing reformulated **Kurt Gödel**'s 1931 results on the limits of proof and computation, replacing Gödel's universal arithmetic-based formal language with the formal and simple hypothetical devices that became known as **Turing machines**. He proved that some such machine would be capable of performing any conceivable mathematical computation if it were representable as an **algorithm**. He went on to prove that there was no solution to the ***Entscheidungsproblem*** by first showing that the **halting problem** for Turing machines is **undecidable**: in general, it is not possible to decide algorithmically whether a given Turing machine will ever halt.

He also introduced the notion of a "universal machine" (now known as a **universal Turing machine**), with the idea that such a machine could perform the tasks of any other machine, or in other words, it is provably capable of computing anything that is computable by executing a program stored on tape, allowing the machine to be programmable. **John von Neumann** acknowledged that the central concept of the modern computer was due to this paper.<sup>[71]</sup> Turing machines are to this day a central object of study in **theory of computation**. Except for the limitations imposed by their finite memory stores, modern computers are said to be **Turing-complete**, which is to say, they have **algorithm** execution capability equivalent to a **universal Turing machine**.

### Electromechanical computers  [ edit ]

*Further information: **Mechanical computer** § **Electro-mechanical computers***

The era of modern computing began with a flurry of development before and during World War II. Most digital computers built in this period were built with electromechanical – electric switches drove mechanical relays to perform the calculation. These mechanical components had a low operating speed due to their mechanical nature and were eventually superseded by much faster all-electric components, originally using **vacuum tubes** and later **transistors**.

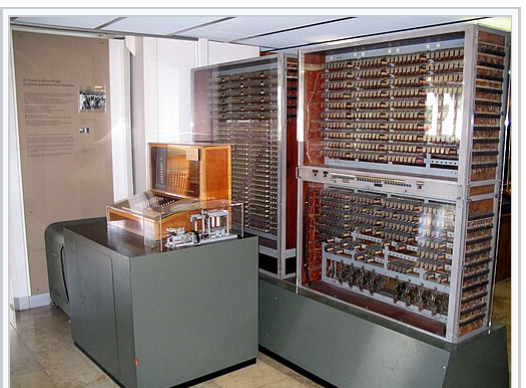

 The **Curta** calculator could also do multiplication and division.

 A portion of **Babbage's Difference Engine**

**Sir William Thomson**'s third tide-predicting machine design, 1879–81

 Parts from four early computers, 1962. From left to right: **ENIAC** board, **EDVAC** board, **ORDVAC** board, and **BRLESC-I** board, showing the trend toward **miniaturization**.



The **Z3** was one of the earliest examples of a electrically operated digital **computer** built with electromechanical relays and was created by civil engineer **Konrad Zuse** in 1940 in Germany. It was an improvement on his earlier, mechanical **Z1**; although it used the same mechanical **memory**, it replaced the arithmetic and control logic with electrical **relay** circuits.<sup>[72]</sup>

In the same year, electro-mechanical devices called **bombes** were built by British **cryptologists** to help decipher **German Enigma-machine**-encrypted secret messages during **World War II**. The bombe's initial design was created in 1939 at the UK **Government Code and Cypher School** at **Bletchley Park** by **Alan Turing**,<sup>[73]</sup> with an important refinement devised in 1940 by **Gordon Welchman**.<sup>[74]</sup> The engineering design and construction was the work of **Harold Keen** of the **British Tabulating Machine Company**. It was a substantial development from a device that had been designed in 1938 by **Polish Cipher Bureau** cryptologist **Marian Rejewski**, and known as the "**cryptologic bomb**" (**Polish**: "*bomba kryptologiczna*").



Replica of **Zuse's Z3**, the first fully automatic, digital (electromechanical) computer

In 1941, Zuse followed his earlier machine up with the **Z3**.<sup>[72]</sup> the world's first working **electromechanical programmable**, fully automatic digital computer.<sup>[75]</sup> The Z3 was built with 2000 **relays**, implementing a 22-bit **word length** that operated at a **clock frequency** of about 5–10 **Hz**.<sup>[76]</sup> Program code and data were stored on punched **film**. It was quite similar to modern machines in some respects, pioneering numerous advances such as **floating-point numbers**. Replacement of the hard-to-implement decimal system (used in **Charles Babbage**'s earlier design) by the simpler **binary** system meant that Zuse's machines were easier to build and potentially more reliable, given the technologies available at that time.<sup>[77]</sup> Despite lacking explicit conditional execution, the Z3 was proven to have been a theoretically **Turing-complete machine** in 1998 by **Raúl Rojas**.<sup>[78]</sup> In two 1936 **patent** applications, Zuse also anticipated that machine instructions could be stored in the same storage used for data—the key insight of what became known as the **von Neumann architecture**, first implemented in 1948 in America in the **electromechanical IBM SSEC** and in Britain in the fully electronic **Manchester Baby**.<sup>[79]</sup>

Zuse suffered setbacks during World War II when some of his machines were destroyed in the course of **Allied** bombing campaigns. Apparently his work remained largely unknown to engineers in the UK and US until much later, although at least IBM was aware of it as it financed his post-war startup company in 1946 in return for an option on Zuse's patents.

In 1944, the **Harvard Mark I** was constructed at IBM's Endicott laboratories.<sup>[80]</sup> It was a similar general purpose electro-mechanical computer to the Z3, but was not quite Turing-complete.

## Digital computation  [edit]

The term digital was first suggested by **George Robert Stibitz** and refers to where a signal, such as a voltage, is not used to directly represent a value (as it would be in an **analog computer**), but to encode it. In November 1937, Stibitz, then working at Bell Labs (1930–1941),<sup>[81]</sup> completed a relay-based calculator he later dubbed the "**Model K**" (for "kitchen table", on which he had assembled it), which became the first **binary adder**.<sup>[82]</sup> Typically signals have two states – low (usually representing 0) and high (usually representing 1), but sometimes **three-valued logic** is used, especially in high-density memory. Modern computers generally use **binary logic**, but many early machines were **decimal computers**. In these machines, the basic unit of data was the decimal digit, encoded in one of several schemes, including **binary-coded decimal** or BCD, **bi-quinary**, **excess-3**, and **two-out-of-five code**.

The mathematical basis of digital computing is **Boolean algebra**, developed by the British mathematician **George Boole** in his work *The Laws of Thought*, published in 1854. His Boolean algebra was further refined in the 1860s by **William Jevons** and **Charles Sanders Peirce**, and was first presented systematically by **Ernst Schröder** and **A. N. Whitehead**.<sup>[83]</sup> In 1879 Gottlob Frege developed the formal approach to logic and proposes the first logic language for logical equations.<sup>[84]</sup>

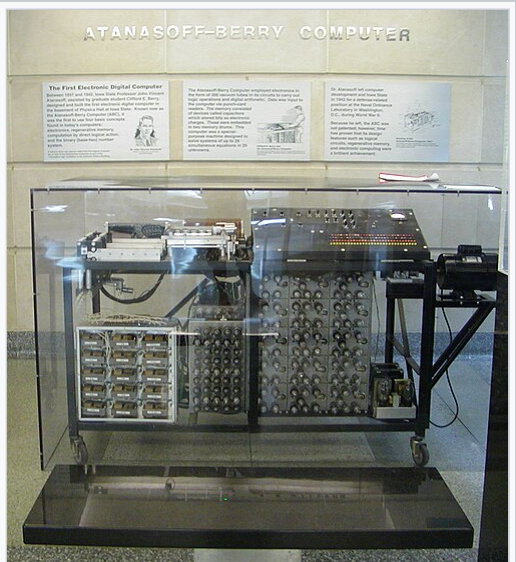
In the 1930s and working independently, American **electronic engineer** **Claude Shannon** and Soviet **logician** **Victor Shestakov** both showed a **one-to-one correspondence** between the concepts of **Boolean logic** and certain electrical circuits, now called **logic gates**, which are now ubiquitous in digital computers.<sup>[85]</sup> They showed that electronic relays and switches can realize the **expressions** of **Boolean algebra**.<sup>[86]</sup> This thesis essentially founded practical **digital circuit** design. In addition Shannon's paper gives a correct circuit diagram for a 4 bit digital binary adder.<sup>[87]</sup>

## Electronic data processing  [edit]

Purely **electronic circuit** elements soon replaced their mechanical and electromechanical equivalents, at the same time that digital calculation replaced analog. Machines such as the **Z3**, the **Atanasoff–Berry Computer**, the **Colossus computers**, and the **ENIAC** were built by hand, using circuits containing relays or valves (vacuum tubes), and often used **punched cards** or **punched paper tape** for input and as the main (non-volatile) storage medium.<sup>[88]</sup>

Engineer **Tommy Flowers** joined the telecommunications branch of the **General Post Office** in 1926. While working at the **research station** in **Dollis Hill** in the 1930s, he began to explore the possible use of electronics for the **telephone exchange**. Experimental equipment that he built in 1934 went into operation 5 years later, converting a portion of the **telephone exchange** network into an electronic data processing system, using thousands of **vacuum tubes**.<sup>[60]</sup>

In the US, in 1940 Arthur Dickinson (IBM) invented the first digital electronic computer.<sup>[89]</sup> This calculating device was fully electronic – control, calculations and output (the first electronic display).<sup>[90]</sup> John Vincent Atanasoff and Clifford E. Berry of Iowa State University developed the Atanasoff–Berry Computer (ABC) in 1942,<sup>[91]</sup> the first binary electronic digital calculating device.<sup>[92]</sup> This design was semi-electronic (electro-mechanical control and electronic calculations), and used about 300 vacuum tubes, with capacitors fixed in a mechanically rotating drum for memory. However, its paper card writer/reader was unreliable and the regenerative drum contact system was mechanical. The machine's special-purpose nature and lack of changeable, **stored program** distinguish it from modern computers.<sup>[93]</sup>



**Atanasoff–Berry Computer** replica at first floor of Durham Center, **Iowa State University**

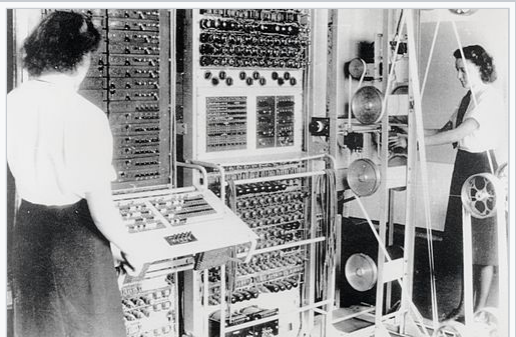
Computers whose logic was primarily built using vacuum tubes are now known as **first generation computers**.

## The electronic programmable computer  [edit]

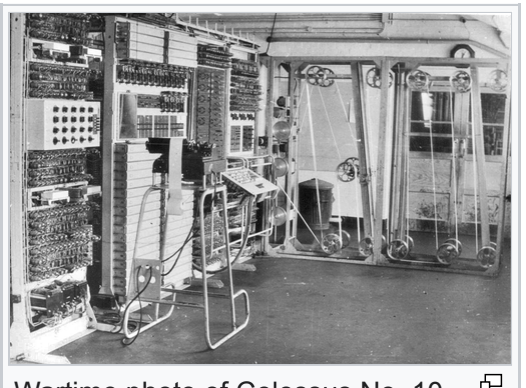
*Main articles: **Colossus computer** and **ENIAC***

During World War II, British codebreakers at **Bletchley Park**, 40 miles (64 km) north of London, achieved a number of successes at breaking encrypted enemy military communications. The German encryption machine, **Enigma**, was first attacked with the help of the electro-mechanical **bombes**.<sup>[94]</sup> They ruled out possible Enigma settings by performing chains of logical deductions implemented electrically. Most possibilities led to a contradiction, and the few remaining could be tested by hand.

The Germans also developed a series of teleprinter encryption systems, quite different from Enigma. The **Lorenz SZ 40/42** machine was used for high-level Army communications, code-named "Tunny" by the British. The first intercepts of Lorenz messages began in 1941. As part of an attack on Tunny, **Max Newman** and his colleagues developed the **Heath Robinson**, a fixed-function machine to aid in code breaking.<sup>[95]</sup> **Tommy Flowers**, a senior engineer at the **Post Office Research Station**<sup>[96]</sup> was recommended to Max Newman by Alan Turing<sup>[97]</sup> and spent eleven months from early February 1943 designing and building the more flexible **Colossus computer** (which superseded the **Heath Robinson**).<sup>[98]</sup><sup>[99]</sup> After a functional test in December 1943, Colossus was shipped to Bletchley Park, where it was delivered on 18 January 1944<sup>[100]</sup> and attacked its first message on 5 February.<sup>[101]</sup> By the time Germany surrendered in May 1945, there were ten **Colossi** working at Bletchley Park.<sup>[102]</sup>



Colossus was the first **electronic digital programmable** computing device, and was used to break German ciphers during World War II. It remained unknown, as a military secret, well into the 1970s.



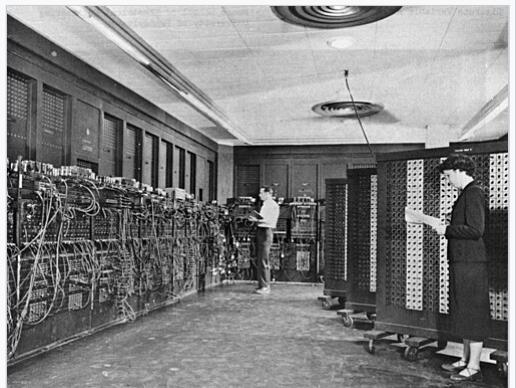
War-time photo of Colossus No. 10

Colossus was the world's first **electronic digital programmable computer**.<sup>[60]</sup> It used a large number of valves (vacuum tubes). It had paper-tape input and was capable of being configured to perform a variety of **Boolean logical** operations on its data,<sup>[103]</sup> but it was not **Turing-complete**. Data input to Colossus was by **photoelectric** reading of a paper tape transcription of the enciphered intercepted message. This was arranged in a continuous loop so that it could be read and re-read multiple times – there being no internal store for the data. The reading mechanism ran at 5,000 characters per second with the paper tape moving at 40 ft/s (12.2 m/s; 27.3 mph). Colossus Mark 1 contained 1500 thermionic valves (tubes), but Mark 2 with 2400 valves and five processors in parallel, was both 5 times faster and simpler to operate than Mark 1, greatly speeding the decoding process. Mark 2 was designed while Mark 1 was being constructed. **Allen Coombs** took over leadership of the Colossus Mark 2 project when **Tommy Flowers** moved on to other projects.<sup>[104]</sup> The first Mark 2 Colossus became operational on 1 June 1944, just in time for the Allied **Invasion of Normandy** on **D-Day**.

Most of the use of Colossus was in determining the start positions of the Tunny rotors for a message, which was called "wheel setting". Colossus included the first-ever use of **shift registers** and **systolic arrays**, enabling five simultaneous tests, each involving up to 100 **Boolean calculations**. This enabled five different possible start positions to be examined for one transit of the paper tape.<sup>[105]</sup> As well as wheel setting some later **Colossi** included mechanisms intended to help determine pin patterns known as "wheel breaking". Both models were programmable using switches and plug panels in a way their predecessors had not been.

Without the use of these machines, the **Allies** would have been deprived of the very valuable **intelligence** that was obtained from reading the vast quantity of **enciphered** high-level **telegraphic** messages between the **German High Command (OKW)** and their **army** commands throughout occupied Europe. Details of their existence, design, and use were kept secret well into the 1970s. **Winston Churchill** personally issued an order for their destruction into pieces no larger than a man's hand, to keep secret that the British were capable of cracking **Lorenz SZ cyphers** (from German rotor stream cipher machines) during the oncoming Cold War. Two of the machines were transferred to the newly formed **GCHQ** and the others were destroyed. As a result, the machines were not included in many histories of computing.<sup>[9]</sup> A reconstructed working copy of one of the Colossus machines is now on display at Bletchley Park.

The **ENIAC** (Electronic Numerical Integrator and Computer) was the first electronic programmable computer built in the US. Although the ENIAC used similar technology to the **Colossi**, it was much faster and more flexible and was Turing-complete. Like the Colossi, a "program" on the ENIAC was defined by the states of its patch cables and switches, a far cry from the **stored-program** electronic machines that came later. Once a program was ready to be run, it had to be mechanically set into the machine with manual resetting of plugs and switches. The programmers of the ENIAC were women who had been trained as mathematicians.<sup>[107]</sup>



**ENIAC** was the first Turing-complete <sup>en</sup> electronic device, and performed ballistics trajectory calculations for the **United States Army**.<sup>[106]</sup>

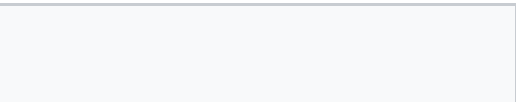
It combined the high speed of electronics with the ability to be programmed for many complex problems. It could add or subtract 5000 times a second, a thousand times faster than any other machine. It also had modules to multiply, divide, and square root. High-speed memory was limited to 20 words (equivalent to about 80 bytes). Built under the direction of **John Mauchly** and **J. Presper Eckert** at the University of Pennsylvania, ENIAC's development and construction lasted from 1943 to full operation at the end of 1945. The machine was huge, weighing 30 tons, using 200 kilowatts of electric power and contained over 18,000 vacuum tubes, 1,500 relays, and hundreds of thousands of resistors, capacitors, and inductors.<sup>[108]</sup> One of its major engineering feats was to minimize the effects of tube burnout, which was a common problem in machine reliability at that time. The machine was in almost constant use for the next ten years.

## Stored-program computer  [edit]

*Main article: **Stored-program computer***

*Further information: **List of vacuum-tube computers***

The theoretical basis for the stored-program computer was proposed by **Alan Turing** in his 1936 paper *On Computable Numbers*.<sup>[70]</sup> Whilst Turing was at **Princeton University** working on his PhD, **John von Neumann** got to know him and became intrigued by his concept of a universal computing machine.<sup>[109]</sup>





Early computing machines executed the set sequence of steps, known as a 'program', that could be altered by changing electrical connections using switches or a **patch panel** (or **plugboard**). However, this process of 'reprogramming' was often difficult and time-consuming, requiring engineers to create flowcharts and physically re-wire the machines.<sup>[110]</sup> Stored-program computers, by contrast, were designed to store a set of instructions (a **program**), in memory – typically the same memory as stored data.

ENIAC inventors **John Mauchly** and **J. Presper Eckert** proposed, in August 1944, the construction of a machine called the Electronic Discrete Variable Automatic Computer (**EDVAC**) and design work for it commenced at the **University of Pennsylvania's Moore School of Electrical Engineering**, before the ENIAC was fully operational. The design implemented a number of important architectural and logical improvements conceived during the ENIAC's construction, and a high-speed **serial-access memory**.<sup>[111]</sup> However, Eckert and Mauchly left the project and its construction floundered.

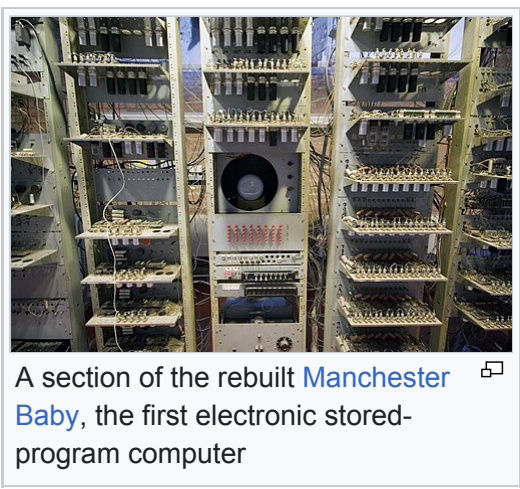
In 1945, von Neumann visited the Moore School and wrote notes on what he saw, which he sent to the project. The U.S. Army liaison there had them typed and circulated as the *First Draft of a Report on the EDVAC*. The draft did not mention Eckert and Mauchly and, despite its incomplete nature and questionable lack of attribution of the sources of some of the ideas,<sup>[60]</sup> the computer architecture it outlined became known as the 'von Neumann architecture'.

In 1945, Turing joined the **UK National Physical Laboratory** and began work on developing an electronic stored-program digital computer. His late-1945 report 'Proposed Electronic Calculator' was the first reasonably detailed specification for such a device. Turing presented a more detailed paper to the **National Physical Laboratory** (NPL) Executive Committee in March 1946, giving the first substantially complete design of a **stored-program computer**, a device that was called the **Automatic Computing Engine** (ACE).

Turing considered that the speed and the size of **computer memory** were crucial elements,<sup>[112]:p. 4</sup> so he proposed a high-speed memory of what would today be called **25 KB**, accessed at a speed of **1 MHz**. The ACE implemented **subroutine** calls, whereas the EDVAC did not, and the ACE also used *Abbreviated Computer Instructions*, an early form of **programming language**.

#### Manchester Baby [ edit ]

*Main article: **Manchester Baby***



The **Manchester Baby** (Small Scale Experimental Machine, SSEM) was the world's first electronic **stored-program computer**. It was built at the **Victoria University of Manchester** by **Frederic C. Williams**, **Tom Kilburn** and Geoff Tootill, and ran its first program on 21 June 1948.<sup>[113]</sup>

The machine was not intended to be a practical computer but was instead designed as a **testbed** for the **Williams tube**, the first **random-access** digital storage device.<sup>[114]</sup> Invented by **Freddie Williams** and **Tom Kilburn**<sup>[115][116]</sup> at the University of Manchester in 1946 and 1947, it was a **cathode-ray tube** that used an effect called **secondary emission** to temporarily store electronic **binary data**, and was used successfully in several early computers.

Described as small and primitive in a 1998 retrospective, the Baby was the first working machine to contain all of the elements essential to a modern electronic computer.<sup>[117]</sup> As soon as it had demonstrated the feasibility of its design, a project was initiated at the university to develop the design into a more usable computer, the **Manchester Mark 1**. The Mark 1 in turn quickly became the prototype for the **Ferranti Mark 1**, the world's first commercially available general-purpose computer.<sup>[118]</sup>

The Baby had a **32-bit word** length and a **memory** of 32 words. As it was designed to be the simplest possible stored-program computer, the only arithmetic operations implemented in **hardware** were **subtraction** and **negation**; other arithmetic operations were implemented in software. The first of three programs written for the machine found the highest **proper divisor** of 2<sup>18</sup> (262,144), a calculation that was known would take a long time to run—and so prove the computer's reliability—by testing every integer from 2<sup>18</sup> − 1 downwards, as division was implemented by repeated subtraction of the divisor. The program consisted of 17 instructions and ran for 52 minutes before reaching the correct answer of 131,072, after the Baby had performed 3.5 million operations (for an effective CPU speed of 1.1 **kIPS**). The successive approximations to the answer were displayed as a pattern of dots on the output **CRT** which mirrored the pattern held on the Williams tube used for storage.

#### Manchester Mark 1 [ edit ]

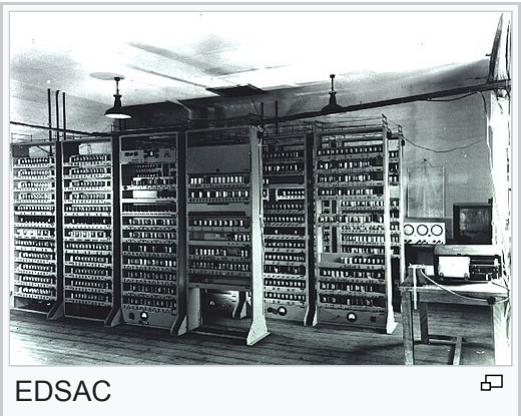
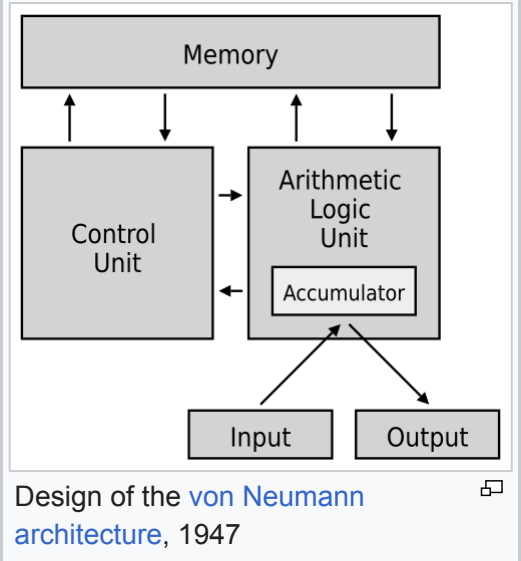
The SSEM led to the development of the **Manchester Mark 1** at the University of Manchester.<sup>[119]</sup> Work began in August 1948, and the first version was operational by April 1949; a program written to search for **Mersenne primes** ran error-free for nine hours on the night of 16/17 June 1949. The machine's successful operation was widely reported in the British press, which used the phrase "electronic brain" in describing it to their readers.

The computer is especially historically significant because of its pioneering inclusion of **index registers**, an innovation which made it easier for a program to read sequentially through an array of **words** in memory. Thirty-four patents resulted from the machine's development, and many of the ideas behind its design were incorporated in subsequent commercial products such as the **IBM 701** and **702** as well as the Ferranti Mark 1. The chief designers, **Frederic C. Williams** and **Tom Kilburn**, concluded from their experiences with the Mark 1 that computers would be used more in scientific roles than in pure mathematics. In 1951 they started development work on **Meg**, the Mark 1's successor, which would include a **floating-point unit**.

#### EDSAC [ edit ]

The other contender for being the first recognizably modern digital stored-program computer<sup>[120]</sup> was the **EDSAC**,<sup>[121]</sup> designed and constructed by **Maurice Wilkes** and his team at the **University of Cambridge Mathematical Laboratory** in **England** at the **University of Cambridge** in 1949. The machine was inspired by **John von Neumann's** seminal *First Draft of a Report on the EDVAC* and was one of the first usefully operational electronic digital **stored-program** computers.<sup>[h]</sup>

EDSAC ran its first programs on 6 May 1949, when it calculated a table of squares<sup>[124]</sup> and a list of **prime numbers**.The EDSAC also served as the basis for the first commercially applied computer, the **LEO I**, used by food manufacturing company **J. Lyons & Co. Ltd.** EDSAC 1 was finally shut down on 11 July 1958, having been superseded by EDSAC 2 which stayed in use until 1965.<sup>[125]</sup>



The "brain" [computer] may one day come down to our level [of the common people] and help with our income-tax and book-keeping calculations. But this is speculation and there is no sign of it so far.

—British newspaper *The Star* in a June 1949 news article about the **EDSAC** computer, long before the era of the personal computers.<sup>[126]</sup>

#### EDVAC [ edit ]

ENIAC inventors **John Mauchly** and **J. Presper Eckert** proposed the **EDVAC's** construction in August 1944, and design work for the EDVAC commenced at the **University of Pennsylvania's Moore School of Electrical Engineering**, before the **ENIAC** was fully operational. The design implemented a number of important architectural and logical improvements conceived during the ENIAC's construction, and a high-speed **serial-access memory**.<sup>[111]</sup> However, Eckert and Mauchly left the project and its construction floundered.

It was finally delivered to the **U.S. Army's Ballistics Research Laboratory** at the **Aberdeen Proving Ground** in August 1949, but due to a number of problems, the computer only began operation in 1951, and then only on a limited basis.

#### Commercial computers [ edit ]

The first commercial electronic computer was the **Ferranti Mark 1**, built by **Ferranti** and delivered to the **University of Manchester** in February 1951. It was based on the **Manchester Mark 1**. The main improvements over the Manchester Mark 1 were in the size of the **primary storage** (using **random access Williams tubes**), **secondary storage** (using a **magnetic drum**), a faster multiplier, and additional instructions. The basic cycle time was 1.2 milliseconds, and a multiplication could be completed in about 2.16 milliseconds. The multiplier used almost a quarter of the machine's 4,050 vacuum tubes (valves).<sup>[127]</sup> A second machine was purchased by the **University of Toronto**, before the design was revised into the **Mark 1 Star**. At least seven of these later machines were delivered between 1953 and 1957, one of them to **Shell** labs in Amsterdam.<sup>[128]</sup>

In October 1947, the directors of **J. Lyons & Company**, a British catering company famous for its teashops but with strong interests in new office management techniques, decided to take an active role in promoting the commercial development of computers. The **LEO I** computer (Lyons Electronic Office) became operational in April 1951<sup>[129]</sup> and ran the world's first regular routine office computer **job**. On 17 November 1951, the J. Lyons company began weekly operation of a bakery valuations job on the LEO – the first business **application** to go live on a stored-program computer.<sup>[i]</sup>

In June 1951, the **UNIVAC I** (Universal Automatic Computer) was delivered to the **U.S. Census Bureau**. Remington Rand eventually sold 46 machines at more than US\$1 million each (\$12.1 million as of 2024).<sup>[130]</sup> UNIVAC was the first "mass-produced" computer. It used 5,200 vacuum tubes and consumed 125 **kW** of power. Its primary storage was **serial-access** mercury delay lines capable of storing 1,000 words of 11 decimal digits plus sign (72-bit words).

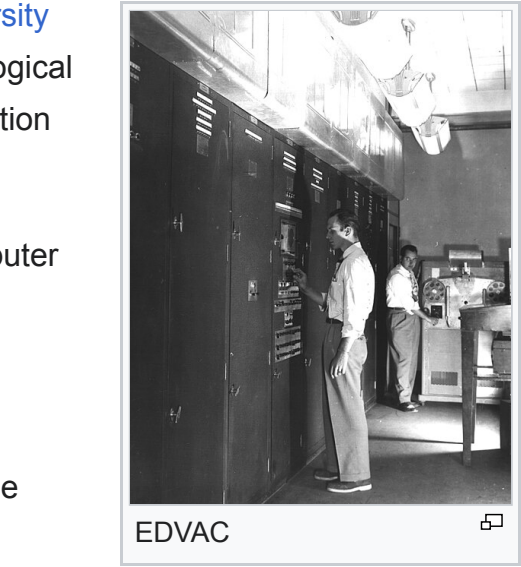
In 1952, **Compagnie des Machines Bull** released the **Gamma 3** computer, which became a large success in Europe, eventually selling more than 1,200 units, and the first kcomputer produced in more than 1,000 units.<sup>[131]</sup> The Gamma 3 had innovative features for its time including a dual-mode, software switchable, BCD and binary ALU, as well as a hardwired floating-point library for scientific computing.<sup>[131]</sup> In its E.T configuration, the Gamma 3 drum memory could fit about 50,000 instructions for a capacity of 16,384 words (around 100 kB), a large amount for the time.<sup>[131]</sup>

Compared to the UNIVAC, IBM introduced a smaller, more affordable computer in 1954 that proved very popular.<sup>[j][133]</sup> The **IBM 650** weighed over 900 kg, the attached power supply weighed around 1350 kg and both were held in separate cabinets of roughly 1.5 × 0.9 × 1.8 m. The system cost US\$500,000<sup>[134]</sup> (\$5.85 million as of 2024) or could be leased for US\$3,500 a month (\$40,000 as of 2024).<sup>[130]</sup> Its drum memory was originally 2,000 ten-digit words, later expanded to 4,000 words. Memory limitations such as this were to dominate programming for decades afterward. The program instructions were fetched from the spinning drum as the code ran. Efficient execution using drum memory was provided by a combination of hardware architecture – the instruction format included the address of the next instruction – and software: the **Symbolic Optimal Assembly Program**, SOAP,<sup>[135]</sup> assigned instructions to the optimal addresses (to the extent possible by static analysis of the source program). Thus many instructions were, when needed, located in the next row of the drum to be read and additional wait time for drum rotation was reduced.

#### Microprogramming [ edit ]

In 1951, British scientist **Maurice Wilkes** developed the concept of **microprogramming** from the realisation that the **central processing unit** of a computer could be controlled by a miniature, highly specialized **computer program** in high-speed **ROM**. Microprogramming allows the base instruction set to be defined or extended by built-in programs (now called **firmware** or **microcode**).<sup>[136]</sup> This concept greatly simplified CPU development. He first described this at the **University of Manchester** Computer Inaugural Conference in 1951, then published in expanded form in *IEEE Spectrum* in 1955.<sup>[*citation needed*]</sup>

It was widely used in the CPUs and **floating-point** units of **mainframe** and other computers; it was implemented for the first time in **EDSAC 2**,<sup>[137]</sup> which also used multiple identical "bit slices" to simplify design. Interchangeable, replaceable tube assemblies were used for each bit of the processor.<sup>[k]</sup>





## Magnetic memory  [edit]

Magnetic **drum memories** were developed for the US Navy during WW II with the work continuing at **Engineering Research Associates** (ERA) in 1946 and 1947. ERA, then a part of Univac included a drum memory in its **1103**, announced in February 1953. The first mass-produced computer, the **IBM 650**, also announced in 1953 had about 8.5 kilobytes of drum memory.

**Magnetic-core** memory patented in 1949<sup>[139]</sup> with its first usage demonstrated for the **Whirlwind computer** in August 1953.<sup>[140]</sup> Commercialization followed quickly. Magnetic core was used in peripherals of the IBM 702 delivered in July 1955, and later in the 702 itself. The **IBM 704** (1955) and the Ferranti Mercury (1957) used magnetic-core memory. It went on to dominate the field into the 1970s, when it was replaced with semiconductor memory. Magnetic core peaked in volume about 1975 and declined in usage and market share thereafter.<sup>[141]</sup>

As late as 1980, PDP-11/45 machines using magnetic-core main memory and drums for swapping were still in use at many of the original UNIX sites.

## Early digital computer characteristics  [edit]

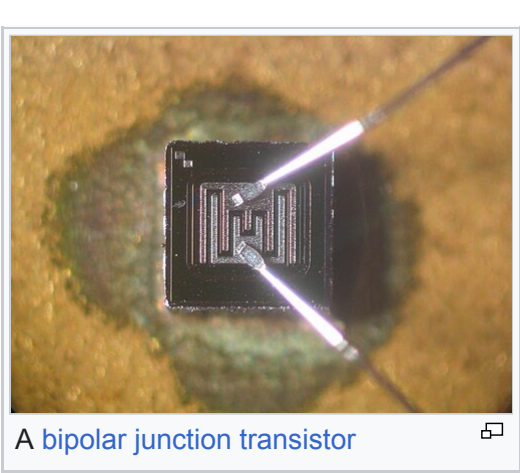
*Further information:* ***Analytical Engine § Comparison to other early computers***

Defining characteristics of some early digital computers of the 1940s (In the history of computing hardware)					
Name	First operational	Numeral system	Computing mechanism	Programming	Turing-complete
<b>Arthur H. Dickinson IBM</b> (US)	Jan 1940	<b>Decimal</b>	<b>Electronic</b>	Not programmable	<b>No</b>
<b>Joseph Desch NCR</b> (US)	March 1940	<b>Decimal</b>	<b>Electronic</b>	Not programmable	<b>No</b>
<b>Zuse Z3</b> (Germany)	May 1941	<b>Binary floating point</b>	<b>Electro-mechanical</b>	Program-controlled by punched 35 mm <b>film stock</b> (but no conditional branch)	In theory (1998)
<b>Atanasoff–Berry Computer</b> (US)	1942	Binary	<b>Electronic</b>	Not programmable — single purpose	<b>No</b>
<b>Colossus Mark 1</b> (UK)	Feb 1944	Binary	Electronic	Program-controlled by patch cables and switches	<b>No</b>
<b>Harvard Mark I – IBM ASCC</b> (US)	May 1944	<b>Decimal</b>	Electro-mechanical	Program-controlled by 24-channel <b>punched paper tape</b> (but no conditional branch)	Debatable
<b>Colossus Mark 2</b> (UK)	June 1944	Binary	Electronic	Program-controlled by patch cables and switches	Conjectured <sup>[142]</sup>
<b>Zuse Z4</b> (Germany)	March 1945	Binary floating point	Electro-mechanical	Program-controlled by punched 35 mm film stock	<b>In 1950</b>
<b>ENIAC</b> (US)	December 1945	Decimal	Electronic	Program-controlled by patch cables and switches	<b>Yes</b>
<b>Modified ENIAC</b> (US)	April 1948	Decimal	Electronic	Read-only stored-programming mechanism using the Function Tables as program <b>ROM</b>	<b>Yes</b>
<b>ARC2 (SEC)</b> (UK)	May 1948	Binary	Electronic	<b>Stored-program</b> in <b>rotating drum memory</b>	<b>Yes</b>
<b>Manchester Baby</b> (UK)	June 1948	Binary	Electronic	<b>Stored-program</b> in <b>Williams cathode-ray tube memory</b>	<b>Yes</b>
<b>Manchester Mark 1</b> (UK)	April 1949	Binary	Electronic	Stored-program in Williams cathode-ray tube memory and <b>magnetic drum</b> memory	<b>Yes</b>
<b>EDSAC</b> (UK)	May 1949	Binary	Electronic	Stored-program in mercury <b>delay-line memory</b>	<b>Yes</b>
<b>CSIRAC</b> (Australia)	Nov 1949	Binary	Electronic	Stored-program in mercury delay-line memory	<b>Yes</b>

## Transistor computers  [edit]

*Main article:* ***Transistor computer***

*Further information:* ***List of transistorized computers***



The bipolar **transistor** was invented in 1947. From 1955 onward transistors replaced **vacuum tubes** in computer designs,<sup>[143]</sup> giving rise to the "second generation" of computers. Compared to vacuum tubes, transistors have many advantages: they are smaller, and require less power than vacuum tubes, so give off less heat. Silicon junction transistors were much more reliable than vacuum tubes and had longer service life. Transistorized computers could contain tens of thousands of binary logic circuits in a relatively compact space. Transistors greatly reduced computers' size, initial cost, and **operating cost**. Typically, second-generation computers were composed of large numbers of **printed circuit boards** such as the **IBM Standard Modular System**,<sup>[144]</sup> each carrying one to four **logic gates** or **flip-flops**.

At the **University of Manchester**, a team under the leadership of **Tom Kilburn** designed and built a machine using the newly developed **transistors** instead of valves. Initially the only devices available were **germanium point-contact transistors**, less reliable than the valves they replaced but which consumed far less power.<sup>[145]</sup> Their first **transistorized computer**, and the first in the world, was **operational by 1953**,<sup>[146]</sup> and a second version was completed there in April 1955.<sup>[146]</sup> The 1955 version used 200 transistors, 1,300 **solid-state diodes**, and had a power consumption of 150 watts. However, the machine did make use of valves to generate its 125 kHz clock waveforms and in the circuitry to read and write on its magnetic drum memory, so it was not the first completely transistorized computer.

That distinction goes to the **Harwell CADET** of 1955,<sup>[147]</sup> built by the electronics division of the **Atomic Energy Research Establishment** at **Harwell**. The design featured a 64-kilobyte magnetic drum memory store with multiple moving heads that had been designed at the **National Physical Laboratory, UK**. By 1953 this team had transistor circuits operating to read and write on a smaller magnetic drum from the **Royal Radar Establishment**. The machine used a low clock speed of only 58 kHz to avoid having to use any valves to generate the clock waveforms.<sup>[148][147]</sup>

CADET used 324-point-contact transistors provided by the UK company **Standard Telephones and Cables**; 76 **junction transistors** were used for the first stage amplifiers for data read from the drum, since point-contact transistors were too noisy. From August 1956, CADET was offering a regular computing service, during which it often executed continuous computing runs of 80 hours or more.<sup>[149][150]</sup> Problems with the reliability of early batches of point contact and alloyed junction transistors meant that the machine's **mean time between failures** was about 90 minutes, but this improved once the more reliable **bipolar junction transistors** became available.<sup>[151]</sup>

The Manchester University Transistor Computer's design was adopted by the local engineering firm of **Metropolitan-Vickers** in their **Metrovick 950**, the first commercial transistor computer anywhere.<sup>[152]</sup> Six Metrovick 950s were built, the first completed in 1956. They were successfully deployed within various departments of the company and were in use for about five years.<sup>[146]</sup> A second generation computer, the **IBM 1401**, captured about one third of the world market. IBM installed more than ten thousand 1401s between 1960 and 1964.

### Transistor peripherals  [edit]

Transistorized electronics improved not only the CPU (Central Processing Unit), but also the **peripheral devices**. The second generation **disk data storage units** were able to store tens of millions of letters and digits. Next to the **fixed disk** storage units, connected to the CPU via high-speed data transmission, were removable disk data storage units. A removable **disk pack** can be easily exchanged with another pack in a few seconds. Even if the removable disks' capacity is smaller than fixed disks, their interchangeability guarantees a nearly unlimited quantity of data close at hand. **Magnetic tape** provided archival capability for this data, at a lower cost than disk.

Many second-generation CPUs delegated peripheral device communications to a secondary processor. For example, while the communication processor controlled **card reading and punching**, the main CPU executed calculations and binary **branch instructions**. One **databus** would bear data between the main CPU and core memory at the CPU's **fetch-execute cycle** rate, and other databusses would typically serve the peripheral devices. On the **PDP-1**, the core memory's cycle time was 5 microseconds; consequently most arithmetic instructions took 10 microseconds (100,000 operations per second) because most operations took at least two memory cycles; one for the instruction, one for the **operand** data fetch.

During the second generation **remote terminal** units (often in the form of **Teleprinters** like a **Friden Flexowriter**) saw greatly increased use.<sup>[1]</sup> Telephone connections provided sufficient speed for early remote terminals and allowed hundreds of kilometers separation between remote-terminals and the computing center. Eventually these stand-alone computer networks would be generalized into an interconnected ***network of networks***—the Internet.<sup>[m]</sup>

### Transistor supercomputers  [edit]

The early 1960s saw the advent of **supercomputing**. The **Atlas** was a joint development between the **University of Manchester**, **Ferranti**, and **Plessey**, and was first installed at Manchester University and officially commissioned in 1962 as one of the world's first **supercomputers** – considered to be the most powerful computer in the world at that time.<sup>[155]</sup> It was said that whenever Atlas went offline half of the United Kingdom's computer capacity was lost.<sup>[156]</sup> It was a second-generation machine, using **discrete germanium transistors**. Atlas also pioneered the **Atlas Supervisor**, "considered by many to be the first recognisable modern **operating system**".<sup>[157]</sup>

In the US, a series of computers at **Control Data Corporation** (CDC) were designed by **Seymour Cray** to use innovative designs and parallelism to achieve superior computational peak performance.<sup>[158]</sup> The **CDC 6600**, released in 1964, is generally considered the first supercomputer.<sup>[159][160]</sup> The CDC 6600 outperformed its predecessor, the **IBM 7030 Stretch**, by about a factor of 3. With performance of about 1 **megaFLOPS**, the CDC 6600 was the world's fastest computer from 1964 to 1969, when it relinquished that status to its successor, the **CDC 7600**.

## Integrated circuit computers  [edit]

*Main article:* ***History of computing hardware (1960s–present) § Third generation***

The "third-generation" of digital electronic computers used **integrated circuit** (IC) chips as the basis of their logic.

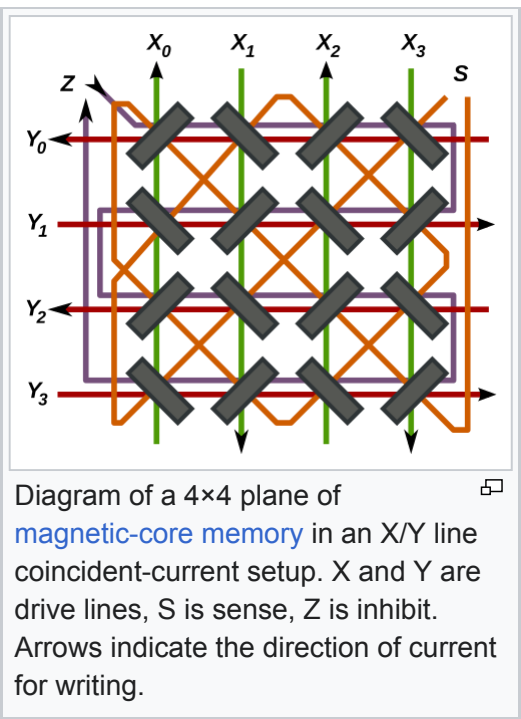
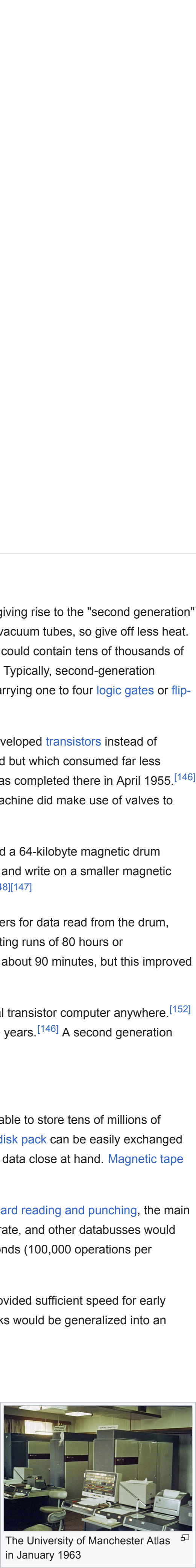


Diagram of a 4×4 plane of magnetic-core memory in an X/Y line coincident-current setup. X and Y are drive lines, S is sense, Z is inhibit. Arrows indicate the direction of current for writing.



The University of Manchester Atlas in January 1963



The idea of an integrated circuit was conceived by a radar scientist working for the **Royal Radar Establishment** of the **Ministry of Defence**, **Geoffrey W.A. Dummer**.

The first working integrated circuits were invented by **Jack Kilby** at **Texas Instruments** and **Robert Noyce** at **Fairchild Semiconductor**.<sup>[161]</sup> Kilby recorded his initial ideas concerning the integrated circuit in July 1958, successfully demonstrating the first working integrated example on 12 September 1958.<sup>[162]</sup> Kilby's invention was a **hybrid integrated circuit** (hybrid IC).<sup>[163]</sup> It had external wire connections, which made it difficult to mass-produce.<sup>[164]</sup>

Noyce came up with his own idea of an integrated circuit half a year after Kilby.<sup>[165]</sup> Noyce's invention was a **monolithic integrated circuit** (IC) chip.<sup>[166][164]</sup> His chip solved many practical problems that Kilby's had not. Produced at Fairchild Semiconductor, it was made of **silicon**, whereas Kilby's chip was made of **germanium**. The basis for Noyce's monolithic IC was Fairchild's **planar process**, which allowed integrated circuits to be laid out using the same principles as those of **printed circuits**. The planar process was developed by Noyce's colleague **Jean Hoerni** in early 1959, based on **Mohamed M. Atalla**'s work on semiconductor surface passivation by silicon dioxide at **Bell Labs** in the late 1950s.<sup>[167][168][169]</sup>

Third generation (integrated circuit) computers first appeared in the early 1960s in computers developed for government purposes, and then in commercial computers beginning in the mid-1960s. The first silicon IC computer was the **Apollo Guidance Computer** or AGC.<sup>[170]</sup> Although not the most powerful computer of its time, the extreme constraints on size, mass, and power of the Apollo spacecraft required the AGC to be much smaller and denser than any prior computer, weighing in at only 70 pounds (32 kg). Each lunar landing mission carried two AGCs, one each in the command and lunar ascent modules.

## Semiconductor memory  <sup>[ edit ]</sup>

*Main article: **Semiconductor memory***

The **MOSFET** (metal–oxide–semiconductor field-effect transistor, or MOS transistor) was invented by **Mohamed M. Atalla** and **Dawon Kahng** at **Bell Labs** in 1959.<sup>[171]</sup> In addition to data processing, the MOSFET enabled the practical use of MOS transistors as **memory cell** storage elements, a function previously served by **magnetic cores**. **Semiconductor memory**, also known as **MOS memory**, was cheaper and consumed less power than **magnetic-core memory**.<sup>[172]</sup> **MOS random-access memory** (RAM), in the form of **static RAM** (SRAM), was developed by John Schmidt at **Fairchild Semiconductor** in 1964.<sup>[172][173]</sup> In 1966, **Robert Dennard** at the **IBM Thomas J. Watson Research Center** developed MOS **dynamic RAM** (DRAM).<sup>[174]</sup> In 1967, Dawon Kahng and **Simon Sze** at Bell Labs developed the **floating-gate MOSFET**, the basis for MOS **non-volatile memory** such as **EPROM**, **EEPROM** and **flash memory**.<sup>[175][176]</sup>

## Microprocessor computers  <sup>[ edit ]</sup>

*Main article: **History of computing hardware (1960s–present) § Fourth generation***

The "fourth-generation" of digital electronic computers used **microprocessors** as the basis of their logic. The microprocessor has origins in the **MOS integrated circuit** (MOS IC) chip.<sup>[177]</sup> Due to rapid **MOSFET scaling**, MOS IC chips rapidly increased in complexity at a rate predicted by **Moore's law**, leading to **large-scale integration** (LSI) with hundreds of transistors on a single MOS chip by the late 1960s. The application of MOS LSI chips to **computing** was the basis for the first microprocessors, as engineers began recognizing that a complete **computer processor** could be contained on a single MOS LSI chip.<sup>[177]</sup>

The subject of exactly which device was the first microprocessor is contentious, partly due to lack of agreement on the exact definition of the term "microprocessor". The earliest multi-chip microprocessors were the **Four-Phase Systems** AL-1 in 1969 and **Garrett AiResearch MP944** in 1970, developed with multiple MOS LSI chips.<sup>[177]</sup> The first single-chip microprocessor was the **Intel 4004**,<sup>[178]</sup> developed on a single **PMOS** LSI chip.<sup>[177]</sup> It was designed and realized by **Ted Hoff**, **Federico Faggin**, **Masatoshi Shima** and **Stanley Mazor** at **Intel**, and released in 1971.<sup>[n]</sup> **Tadashi Sasaki** and **Masatoshi Shima** at **Busicom**, a calculator manufacturer, had the initial insight that the CPU could be a single MOS LSI chip, supplied by Intel.<sup>[180][178]</sup>

While the earliest microprocessor ICs literally contained only the processor, i.e. the central processing unit, of a computer, their progressive development naturally led to chips containing most or all of the internal electronic parts of a computer. The integrated circuit in the image on the right, for example, an **Intel 8742**, is an **8-bit microcontroller** that includes a CPU running at 12 MHz, 128 bytes of **RAM**, 2048 bytes of **EPROM**, and **I/O** in the same chip.

During the 1960s, there was considerable overlap between second and third generation technologies.<sup>[o]</sup> IBM implemented its **IBM Solid Logic Technology** modules in **hybrid circuits** for the IBM System/360 in 1964. As late as 1975, Sperry Univac continued the manufacture of second-generation machines such as the UNIVAC 494. The **Burroughs large systems** such as the B5000 were **stack machines**, which allowed for simpler programming. These **pushdown automaton**s were also implemented in minicomputers and microprocessors later, which influenced programming language design. Minicomputers served as low-cost computer centers for industry, business and universities.<sup>[181]</sup> It became possible to simulate analog circuits with the *simulation program with integrated circuit emphasis*, or **SPICE** (1971) on minicomputers, one of the programs for electronic design automation (**EDA**). The microprocessor led to the development of **microcomputers**, small, low-cost computers that could be owned by individuals and small businesses. Microcomputers, the first of which appeared in the 1970s, became ubiquitous in the 1980s and beyond.

While which specific product is considered the first microcomputer system is a matter of debate, one of the earliest is R2E's **Micral N** (**François Gernelle**, **André Truong**) launched "early 1973" using the Intel 8008.<sup>[182]</sup> The first commercially available microcomputer kit was the **Intel 8080**-based **Altair 8800**, which was announced in the January 1975 cover article of ***Popular Electronics***. However, the Altair 8800 was an extremely limited system in its initial stages, having only 256 bytes of **DRAM** in its initial package and no input-output except its toggle switches and LED register display. Despite this, it was initially surprisingly popular, with several hundred sales in the first year, and demand rapidly outstripped supply. Several early third-party vendors such as **Cromemco** and **Processor Technology** soon began supplying additional **S-100 bus** hardware for the Altair 8800.

In April 1975, at the **Hannover Fair**, **Olivetti** presented the **P6060**, the world's first complete, pre-assembled personal computer system. The central processing unit consisted of two cards, code named PUCE1 and PUCE2, and unlike most other personal computers was built with **TTL** components rather than a microprocessor. It had one or two 8" **floppy disk** drives, a 32-character **plasma display**, 80-column graphical **thermal printer**, 48 Kbytes of **RAM**, and **BASIC** language. It weighed 40 kg (88 lb). As a complete system, this was a significant step from the Altair, though it never achieved the same success. It was in competition with a similar product by IBM that had an external floppy disk drive.

From 1975 to 1977, most microcomputers, such as the **MOS Technology KIM-1**, the **Altair 8800**, and some versions of the **Apple I**, were sold as kits for do-it-yourselfers. Pre-assembled systems did not gain much ground until 1977, with the introduction of the **Apple II**, the Tandy **TRS-80**, the first **SWTPC** computers, and the **Commodore PET**. Computing has evolved with microcomputer architectures, with features added from their larger brethren, now dominant in most market segments.

A NeXT Computer and its **object-oriented** development tools and libraries were used by **Tim Berners-Lee** and **Robert Cailliau** at **CERN** to develop the world's first **web server** software, **CERN httpd**, and also used to write the first **web browser**, **WorldWideWeb**.

Systems as complicated as computers require very high **reliability**. ENIAC remained on, in continuous operation from 1947 to 1955, for eight years before being shut down. Although a vacuum tube might fail, it would be replaced without bringing down the system. By the simple strategy of never shutting down ENIAC, the failures were dramatically reduced. The vacuum-tube **SAGE** air-defense computers became remarkably reliable – installed in pairs, one off-line, tubes likely to fail did so when the computer was intentionally run at reduced power to find them. **Hot-pluggable** hard disks, like the hot-pluggable vacuum tubes of yesteryear, continue the tradition of repair during continuous operation. Semiconductor memories routinely have no errors when they operate, although operating systems like Unix have employed memory tests on start-up to detect failing hardware. Today, the requirement of reliable performance is made even more stringent when **server farms** are the delivery platform.<sup>[183]</sup> Google has managed this by using fault-tolerant software to recover from hardware failures, and is even working on the concept of replacing entire server farms on-the-fly, during a service event.<sup>[184][185]</sup>

In the 21st century, **multi-core** CPUs became commercially available.<sup>[186]</sup> **Content-addressable memory** (CAM)<sup>[187]</sup> has become inexpensive enough to be used in networking, and is frequently used for on-chip **cache memory** in modern microprocessors, although no computer system has yet implemented hardware CAMs for use in programming languages. Currently, CAMs (or associative arrays) in software are programming-language-specific. Semiconductor memory cell arrays are very regular structures, and manufacturers prove their processes on them; this allows price reductions on memory products. During the 1980s, **CMOS logic gates** developed into devices that could be made as fast as other circuit types; computer power consumption could therefore be decreased dramatically. Unlike the continuous current draw of a gate based on other logic types, a CMOS gate only draws significant current, except for leakage, during the 'transition' between logic states.<sup>[188]</sup>

CMOS circuits have allowed computing to become a commercial **product** which is now ubiquitous, embedded in **many forms**, from greeting cards and **telephones** to **satellites**. The **thermal design power** which is dissipated during operation has become as essential as computing speed of operation. In 2006 servers consumed 1.5% of the total U.S. electricity consumption.<sup>[189]</sup> The energy consumption of computer data centers was expected to double to 3% of world consumption by 2011. The **SoC** (system on a chip) has compressed even more of the **integrated circuitry** into a single chip; SoCs are enabling phones and PCs to converge into single hand-held wireless **mobile devices**.<sup>[190]</sup>

**Quantum computing** is an emerging technology in the field of computing. *MIT Technology Review* reported 10 November 2017 that IBM has created a 50-**qubit** computer; currently its quantum state lasts 50 microseconds.<sup>[191]</sup> Google researchers have been able to extend the 50 microsecond time limit, as reported 14 July 2021 in *Nature*;<sup>[192]</sup> stability has been extended 100-fold by spreading a single logical qubit over chains of data qubits for **quantum error correction**.<sup>[192]</sup> *Physical Review X* reported a technique for 'single-gate sensing as a viable readout method for spin qubits' (a singlet-triplet spin state in silicon) on 26 November 2018.<sup>[193]</sup> A Google team has succeeded in operating their RF pulse modulator chip at 3 **kelvins**, simplifying the cryogenics of their 72-qubit computer, which is set up to operate at 0.3 **K**; but the readout circuitry and another driver remain to be brought into the cryogenics.<sup>[194][p]</sup> See: ***Quantum supremacy***<sup>[196][197]</sup> Silicon qubit systems have demonstrated **entanglement** at **non-local** distances.<sup>[198]</sup>

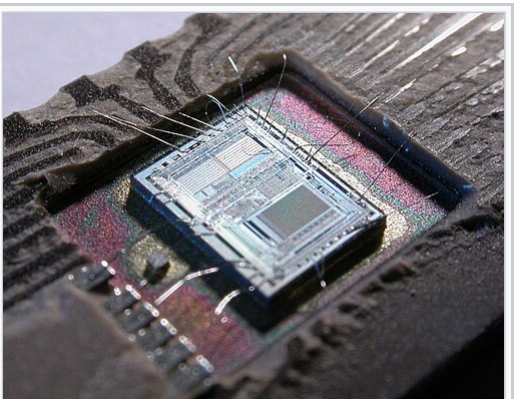
Computing hardware and its software have even become a metaphor for the operation of the universe.<sup>[199]</sup>

## Epilogue  <sup>[ edit ]</sup>

An indication of the rapidity of development of this field can be inferred from the history of the seminal 1947 article by Burks, Goldstine and von Neumann.<sup>[200]</sup> By the time that anyone had time to write anything down, it was obsolete. After 1945, others read John von Neumann's *First Draft of a Report on the EDVAC*, and immediately started implementing their own systems. To this day, the rapid pace of development has continued, worldwide.<sup>[q][r]</sup>

## See also  <sup>[ edit ]</sup>

- Antikythera mechanism**
- History of computing**
- History of computing hardware (1960s–present)**
- History of laptops**
- History of personal computers**
- History of software**
- History of supercomputing**


 The die from an Intel 8742, an 8-bit microcontroller that includes a CPU running at 12 MHz, RAM, EPROM, and I/O




- Information Age
- IT History Society
- Retrocomputing
- Timeline of computing
- List of pioneers in computer science
- Vacuum-tube computer

## Notes [\[ edit \]](#)

- a. <sup>^</sup> The [Ishango bone](#) is a [bone tool](#), dated to the [Upper Paleolithic](#) era, about 18,000 to 20,000 BC. It is a dark brown length of bone, the [fibula](#) of a baboon. It has a series of tally marks carved in three columns running the length of the tool. It was found in 1960 in Belgian Congo.<sup>[1]</sup>
- b. <sup>^</sup> According to [Schmandt-Besserat 1981](#), these clay containers contained tokens, the total of which were the count of objects being transferred. The containers thus served as something of a [bill of lading](#) or an accounts book. In order to avoid breaking open the containers, first, clay impressions of the tokens were placed on the outside of the containers, for the count; the shapes of the impressions were abstracted into stylized marks; finally, the abstract marks were systematically used as numerals; these numerals were finally formalized as numbers. Eventually (Schmandt-Besserat estimates it took 5000 years.<sup>[5]</sup>) the marks on the outside of the containers were all that were needed to convey the count, and the clay containers evolved into clay tablets with marks for the count.
- c. <sup>^</sup> Robson has recommended at least one supplement to [Schmandt-Besserat \(1981\)](#), e.g., a review, Englund, R. (1993). "The origins of script". *Science*. **260** (5114): 1670–1671. doi:10.1126/science.260.5114.1670 <sup>↗</sup>. PMID 17810210 <sup>↗</sup>.<sup>[7]</sup>
- d. <sup>^</sup> A Spanish implementation of [Napier's bones](#) (1617), is documented in [Montaner & Simon 1887](#), pp. 19–20.
- e. <sup>^</sup> All nine machines are described in [Vidal & Vogt 2011](#).
- f. <sup>^</sup> [Binary-coded decimal](#) (BCD) is a numeric representation, or [character encoding](#), which is still widely used.
- g. <sup>^</sup> The existence of Colossus was kept secret by the UK Government for 30 years and so was not known to American computer scientists, such as [Gordon Bell](#) and [Allen Newell](#). And was not in [Bell & Newell \(1971\) \*Computing Structures\*](#), a standard reference work in the 1970s.
- h. <sup>^</sup> The Manchester Baby predated EDSAC as a [stored-program computer](#), but was built as a test bed for the [Williams tube](#) and not as a machine for practical use.<sup>[122]</sup> However, the Manchester Mark 1 of 1949 (not to be confused with the 1948 prototype, the Baby) was available for university research in April 1949 despite being still under development.<sup>[123]</sup>
- i. <sup>^</sup> [Martin 2008](#), p. 24 notes that [David Caminer](#) (1915–2008) served as the first corporate electronic systems analyst, for this first business computer system. LEO would calculate an employee's pay, handle billing, and other office automation tasks.
- j. <sup>^</sup> For example, Kara Platon's article on [Donald Knuth](#) stated that "there was something special about the IBM 650".<sup>[132]</sup>
- k. <sup>^</sup> The microcode was implemented as *extracode* on Atlas.<sup>[138]</sup>
- l. <sup>^</sup> [Allen Newell](#) used remote terminals to communicate cross-country with the [RAND](#) computers.<sup>[153]</sup>
- m. <sup>^</sup> [Bob Taylor](#) conceived of a generalized protocol to link together multiple networks to be viewed as a single session regardless of the specific network: "Wait a minute. Why not just have one terminal, and it connects to anything you want it to be connected to? And, hence, the Arpanet was born."<sup>[154]</sup>
- n. <sup>^</sup> The Intel 4004 (1971) die was 12 mm<sup>2</sup>, composed of 2300 transistors; by comparison, the Pentium Pro was 306 mm<sup>2</sup>, composed of 5.5 million transistors.<sup>[179]</sup>
- o. <sup>^</sup> In the defense field, considerable work was done in the computerized implementation of equations such as [Kalman 1960](#), pp. 35–45.
- p. <sup>^</sup> IBM's 127-qubit computer cannot be simulated on traditional computers.<sup>[195]</sup>
- q. <sup>^</sup> *DBLP* summarizes the *Annals of the History of Computing*, year by year, back to 1979.<sup>[201]</sup>
- r. <sup>^</sup> The fastest *supercomputer* of the [top 500](#) is now Frontier (of Oak Ridge National Laboratory) at 1.102 ExaFlops.<sup>[202]</sup> which is 2.66 times faster than Fugaku, now number two of the top 500.<sup>[203]</sup>

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