1. Types of Computers

Contents

1 Classes of computers **1**

1.1 Classes by size . . . 1

1.1.1 Microcomputers (personal computers) . . . 1

1.1.2 Minicomputers (midrange computers) . . . 1

1.1.3 Mainframe computers . . . 1

1.1.4 Supercomputers . . . 1

1.2 Classes by function . . . 2

1.2.1 Servers . . . 2

1.2.2 Workstations . . . 2

1.2.3 Information appliances . . . 2

1.2.4 Embedded computers . . . 2

1.3 See also . . . 2

1.4 References . . . 2

1.5 External links . . . 2

2 List of computer size categories **3**

2.1 Supercomputers . . . 3

2.2 Mainframe computers . . . 3

2.3 Minicomputers . . . 3

2.4 Microcomputers . . . 3

2.5 Mobile computers . . . 3

2.6 Others . . . 4

2.7 Distinctive marks . . . 4

2.8 Categories . . . 4

2.9 See also . . . 4

2.10 References . . . 4

3 Torpedo Data Computer **5**

3.1 Background . . . 6

3.1.1 History . . . 6

3.1.2 The problem of aiming a straight-running torpedo . . . 6

3.1.3 TDC functional description . . . 7

3.2 Notes and references . . . 9

3.3 External links 10

4 Analog computer **11**

4.1 Setup 11

4.2 Timeline of analog computers 11

4.2.1 Precursors 11

4.2.2 Modern era 12

4.3 Electronic analog computers 13

4.4 Analog–digital hybrid computers and hybrid computing devices 14

4.5 Implementations 15

4.5.1 Mechanical analog computers 15

4.5.2 Electronic analog computers 16

4.6 Components 17

4.7 Limitations 17

4.8 Decline 18

4.9 Practical examples 18

4.10 See also 18

4.11 Notes 18

4.12 References 19

4.13 External links 19

5 Deltar **20**

6 History of computing hardware **21**

6.1 Early devices 21

6.1.1 Ancient era 21

6.1.2 Medieval calculating tools 22

6.1.3 Mechanical calculators 22

6.1.4 Punched card data processing 23

6.1.5 Calculators 23

6.2 First general-purpose computing device 24

6.3 Analog computers 25

6.4 Advent of the digital computer 26

6.4.1 Electromechanical computers 26

6.4.2 Digital computation 27

6.4.3 Electronic data processing 27

6.4.4 The electronic programmable computer 28

6.5 The stored-program computer 29

6.5.1 Theory 29

6.5.2 Manchester “baby” 30

6.5.3 Manchester Mark 1 30

6.5.4 EDSAC 31

6.5.5 EDVAC 31
6.5.6 Commercial computers 31
6.5.7 Microprogramming 32
6.5.8 Magnetic storage 32
6.6 Early computer characteristics 32
6.7 Transistor computers 32
6.7.1 Transistorized peripherals 33
6.7.2 Supercomputers 33
6.8 The integrated circuit 34
6.9 Post-1960 (integrated circuit based) 34
6.10 Future 35
6.11 See also 35
6.12 Notes 36
6.13 References 39
6.14 Further reading 42
6.15 External links 42

7 Instructions per second 44
7.1 Thousand instructions per second 44
7.2 Millions of instructions per second 44
7.3 Timeline of instructions per second 45
7.4 Historic data 45
7.5 See also 45
7.6 References 45
7.7 Text and image sources, contributors, and licenses 48
7.7.1 Text 48
7.7.2 Images 50
7.7.3 Content license 51

Chapter 1

Classes of computers

Computers can be classified, or typed, in many ways. Some common classifications are summarized below. For others see Category:Classes of computers.

1.1 Classes by size

1.1.1 Microcomputers (personal computers)

Microcomputers are the most common kind of computers in use as of 2014. The term "microcomputer" was introduced with the advent of systems based on single chip microprocessors. The best-known early system was the Altair 8800, introduced in 1975. The term "microcomputer" has practically become an anachronism.

These computers include:

- **Desktop computers** – A case and a display, put under and on a desk.
- **In-car computers (carputers)** – Built into a car, for entertainment, navigation, etc.
- **Game consoles** – Fixed computers specialized for entertainment purposes (video games).

Smaller microcomputers are also called mobile devices:

- **Laptops and notebook computers** – Portable and all in one case.
- **Tablet computer** – Like laptops, but with a touchscreen, entirely replacing the physical keyboard.
- **Smartphones, smartbooks, PDAs and palmtop computers** – Small handheld computers with limited hardware.
- **Programmable calculator**– Like small handhelds, but specialized on mathematical work.
- **Handheld game consoles** – The same as game consoles, but small and portable.

1.1.2 Minicomputers (midrange computers)

Minicomputers (colloquially, **minis**) are a class of multi-user computers that lie in the middle range of the computing spectrum, in between the smallest mainframe computers and the largest single-user systems (microcomputers or personal computers). The term **superminicomputer** or **supermini** was used to distinguish more powerful minicomputers that approached mainframes in capability. Superminis were usually 32-bit at a time when most minicomputers were 16-bit. The contemporary term for minicomputer is midrange computer, such as the higher-end SPARC, POWER and Itanium-based systems from Oracle Corporation, IBM and Hewlett-Packard.

1.1.3 Mainframe computers

The term mainframe computer was created to distinguish the traditional, large, institutional computer intended to service multiple users from the smaller, single user machines. These computers are capable of handling and processing very large amounts of data quickly. Mainframe computers are used in large institutions such as government, banks and large corporations. They are measured in MIPS (million instructions per second) and respond to up to 100s of millions of users at a time.

1.1.4 Supercomputers

A Supercomputer is focused on performing tasks involving intense numerical calculations such as weather forecasting, fluid dynamics, nuclear simulations, theoretical astrophysics, and complex scientific computations. A supercomputer is a computer that is at the front-line of current processing capacity, particularly speed of calculation. The term supercomputer itself is rather fluid, and the speed of today's supercomputers tends to become typical of tomorrow's ordinary computer. Supercomputer processing speeds are measured in floating point operations per second, or FLOPS. An example of a floating point operation is the calculation of mathematical equations in real numbers. In terms of computational capability, memory size and speed, I/O technology, and topological issues such as bandwidth and latency, supercomputers are the most powerful, are very expensive, and not cost-effective just to perform batch or transaction processing. Transaction processing is handled by less powerful computers such as server computers or mainframes.

1.2 Classes by function

1.2.1 Servers

Server usually refers to a computer that is dedicated to provide a service. For example, a computer dedicated to a database may be called a "database server". "file servers" manage a large collection of computer files. "Web servers" process web pages and web applications. Many smaller servers are actually personal computers that have been dedicated to provide services for other computers.

1.2.2 Workstations

Workstations are computers that are intended to serve one user and may contain special hardware enhancements not found on a personal computer. By the mid 1990s personal computers reached the processing capabilities of Mini computers and Workstations. Also, with the release of multi-tasking systems such as OS/2, Windows NT and Linux, the operating systems of personal computers could do the job of this class of machines.

1.2.3 Information appliances

Information appliances are computers specially designed to perform a specific "user-friendly" function—such as playing music, photography, or editing text. The term is most commonly applied to mobile devices, though there are also portable and desktop devices of this class.

1.2.4 Embedded computers

Embedded computers are computers that are a part of a machine or device. Embedded computers generally execute a program that is stored in non-volatile memory and is only intended to operate a specific machine or device. Embedded computers are very common. Embedded computers are typically required to operate continuously without being reset or rebooted, and once employed in their task the software usually cannot be modified. An automobile may contain a number of embedded computers; however, a washing machine and a DVD player would contain only one. The central processing units (CPUs) used in embedded computers are often sufficient only for the computational requirements of the specific application and may be slower and cheaper than CPUs found in a personal computer.

1.3 See also

- List of computer size categories

1.4 References

1.5 External links

Four types of Computers

Chapter 2

List of computer size categories

This **list of computer size categories** attempts to list commonly used categories of computer by size, in descending order of size. Of course, one generation's "supercomputer" is the next generation's "mainframe", and a "PDA" does not have the same set of functions as a "laptop", but the list should have some recognition value. It also ranks some more obscure computer sizes.

2.1 Supercomputers

- Minisupercomputer

2.2 Mainframe computers

Mainframe computers are large and expensive but powerful, so they can handle hundreds and thousands of connected users at the same time.

2.3 Minicomputers

- Superminicomputer
- Minicluster (SFF / ITX)[1]
- Server
- Workstation

2.4 Microcomputers

- Tower PC
- Mid-Tower PC
- Mini-Tower PC
- Server
- Workstation
- Personal computer (PC)
  - Desktop computer—see computer form factor for some standardized sizes of desktop computers
  - Home computer

2.5 Mobile computers

- Desktop replacement computer or desknote
- Laptop computer
  - Notebook computer
    - Subnotebook computer, also known as a Kneetop computer; clamshell varieties may also be known as minilaptop or ultraportable laptop computers
- Tablet personal computer
- Slabtop computers including "word-processing keyboards" and the TRS-80 Model 100
- Handheld computers, which include the classes:
  -
    - Ultra-mobile personal computer, or UMPC
    - Personal digital assistant or enterprise digital assistant, which include:
      - HandheldPC or Palmtop computer
      - Pocket personal computer
    - Electronic organizer
    - Pocket computer
    - Calculator, which includes the class:
      - Graphing calculator
      - Scientific calculator
      - Programmable calculator
      - Accounting / Financial Calculator
    - Handheld game console
    - Portable media player
    - Portable data terminal
    - Information appliance
      - Smartphone, a class of mobile phone
      - Feature phone

- Wearable computer
- Single board computer
- Wireless sensor network components
- Plug computer
- Microcontroller
- Smartdust
- Nanocomputer

2.6 Others

- Deskside computer - often strd. rack width but less than half of the typical rack height, esp. for mid-range servers (e.g. RS/6000 7025-F80), visualisation (e.g. Onyx Deskside) or vector processing (e.g. SX-6i).
- Cart computer
- Microsoft Sphere
- Rackmount/Framemount computer
    - Multimedia server
    - Blade server
    - Blade PC
- Small form factor personal computer (SFF, ITX, DTX.etc.)

2.7 Distinctive marks

The classes above are not rigid; there are "edge devices" in most of them. For instance, the "subnotebook" category can usually be distinguished from the "PDA" category because a subnotebook has a keyboard and a PDA has not; however, tablet PCs may be larger than subnotebooks (making it seemingly correct to classify them as laptops) and also lack a keyboard, while devices such as the Handspring Treo 600 have something that might charitably be called a keyboard, but are still definitely in the "smartphone" category.

In the higher end of the spectrum, this informal rule might help:

- You can throw a laptop
- You can lift a workstation
- You can tilt a minicomputer
- You cannot move a mainframe

2.8 Categories

- Category:Supercomputers
- Category:Mainframe computers
- Category:Minicomputers
- Category:Desktop computers
- Category:Cart computers
- Category:Portable computers
- Category:Mobile computers
    - Category:Desktop replacement computers
    - Category:Laptops
        - Category:Notebooks
    - Category:Tablet computers
    - Category:Subnotebooks
    - Category:Handheld computers
        - Category:Pocket computers
        - Category:Personal digital assistants
        - Category:Enterprise Digital Assistants
        - Category:Handheld PCs
            - Category:Palmtops
        - Category:Calculators
        - Category:Handheld game consoles
        - Category:Pocket PCs
        - Category:Portable data terminals
        - Category:Electronic organizers
        - Category:Information appliances
    - Category:Wearable computers
- Category:Embedded systems
- Category:Wireless sensor network
- Category:Smartdust
- Category:Nanocomputer

2.9 See also

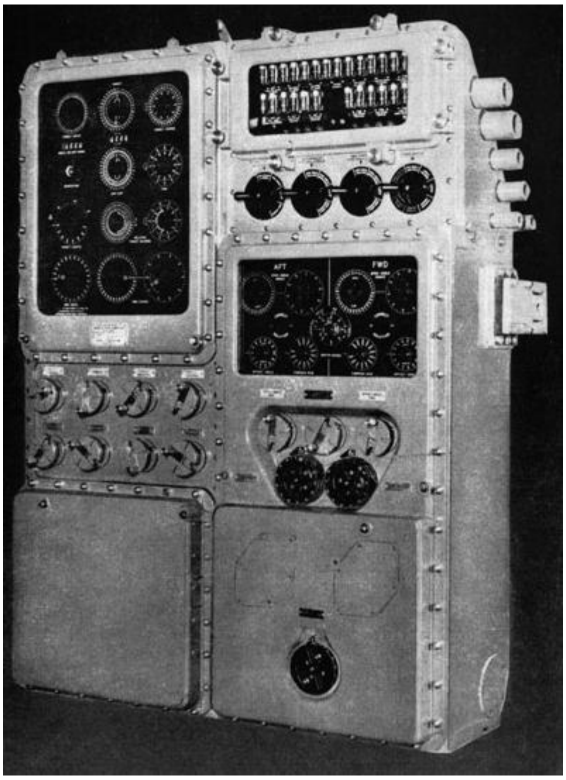
- Classes of computers
- Computer form factor

2.10 References

[1] "minicluster". Archived from the original on 2012-09-06.)

Chapter 3

Torpedo Data Computer



U.S. Navy Mk III Torpedo Data Computer, the standard US Navy torpedo fire control computer during World War II. Later in World War II (1943), the TDC Mk III was replaced by the TDC Mk IV, which was an improved and larger version of the Mk III.

The **Torpedo Data Computer (TDC)** was an early electromechanical analog computer used for torpedo fire-control on American submarines during World War II. Britain, Germany, and Japan also developed automated torpedo fire control equipment, but none were as advanced as the US Navy's TDC,[1] as it was able to automatically track the target rather than simply offering an instantaneous firing solution. This unique capability of the TDC set the standard for submarine torpedo fire control during World War II.[2][3]

Replacing the previously standard hand-held slide rule-type devices (known as the "banjo" & "is/was"),[4] the TDC was designed to provide fire-control solutions for submarine torpedo firing against ships running on the surface (surface warships used a different computer).[5] It had an array of handcranks, dials, and switches for data input and display.[6] To generate a fire control solution, it required inputs on

- submarine course and speed, which were read automatically from the submarine's gyrocompass and pitometer log
- estimated target course, speed, and range information (obtained using data from the submarine's periscope, Target Bearing Transmitter (TBT),[7] radar, and sonar)
- torpedo type and speed (type was needed to deal with the different torpedo ballistics)

The TDC performed the trigonometric calculations required to compute a target intercept course for the torpedo. It also had an electromechanical interface to the torpedoes, allowing it to automatically set courses while torpedoes were still in their tubes, ready to be fired.

The TDC's target tracking capability was used by the fire control party to continuously update the fire control solution even while the submarine was maneuvering. The TDC's target tracking ability also allowed the submarine to accurately fire torpedoes even when the target was temporarily obscured by smoke or fog.

The TDC was a rather bulky addition to the sub's conning tower and required two extra crewmen: one as an expert in its maintenance, the other as its actual operator. Despite these drawbacks, the use of the TDC was an important factor in the successful commerce raiding program conducted by American submarines during the Pacific campaign of World War II. Accounts of the American submarine campaign in the Pacific often cite the use of TDC.[8][9] Some officers became highly skilled in its use,[10] and the navy set up a training school for its use.[11]

Two upgraded World War II-era U.S. Navy fleet submarines (USS *Tusk* and *Cutlass*) with their TDCs continue to serve with Taiwan's navy and U.S. Nautical Museum staff are assisting them with maintaining their equipment.[12] The museum also has a fully restored and functioning TDC from USS *Pampanito*, docked in San Francisco.

3.1 Background

3.1.1 History

The problem of aiming a torpedo has occupied military engineers since Robert Whitehead developed the modern torpedo in the 1860s. These early torpedoes ran at a preset depth on a straight course (consequently they are frequently referred to as “straight runners”). This was the state of the art in torpedo guidance until the development of the homing torpedo during the latter part of World War II.[13] The vast majority of submarine torpedoes during World War II were straight running and these continued in use for many years after World War II.[14] In fact, two World War II-era straight running torpedoes — fired by the British nuclear-powered submarine HMS *Conqueror* — sank the ARA *General Belgrano* in 1982.

During World War I, computing a target intercept course for a torpedo was a manual process where the fire control party was aided by various slide rules[15] (the U.S. examples were colloquially called “banjo”, for its shape, and “Is/Was”, for predicting where a target will be based on where it is and was)[16] or mechanical calculator/sights.[17] These were often “woefully inaccurate”,[18] which helps explain why torpedo spreads were advised.

During World War II, Germany,[19] Japan,[20] and the United States each developed analog computers to automate the process of computing the required torpedo course.[21]

In 1932, the Bureau of Ordnance (BuOrd) initiated development of the TDC with Arma Corporation and Ford Instruments.[22] This culminated in the “very complicated” Mark 1 in 1938.[22] This was retrofitted into older boats, beginning with *Dolphin* and up through the newest *Salmons*.[22]

The first submarine designed to use the TDC was *Tambor*,[23] launched in 1940 with the Mark III, located in the conning tower.[22] (This differed from earlier outfits.)[24] It proved to be the best torpedo fire control system of World War II.[25]

In 1943, the Torpedo Data Computer Mark IV was developed to support the Mark 18 torpedo.[26][27]

Both the Mk III and Mk IV TDC were developed by Arma Corporation (now American Bosch Arma).

3.1.2 The problem of aiming a straight-running torpedo

A straight-running torpedo has a gyroscope-based control system that ensures that the torpedo will run a straight course. The torpedo can run on a course different from that of the submarine by adjusting a parameter called the gyro angle, which sets the course of the torpedo relative to

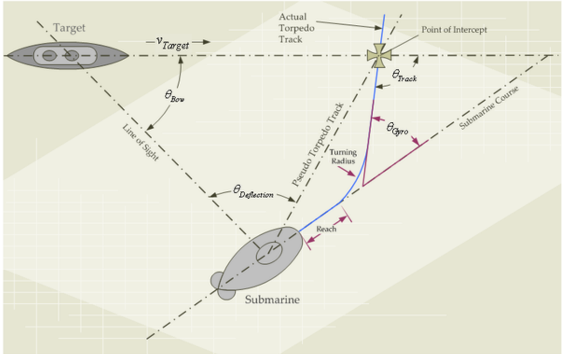


Figure 2: Illustration of general torpedo fire-control problem

the course of the submarine (see Figure 2). The primary role of the TDC is to determine the gyro angle setting required to ensure that the torpedo will strike the target.

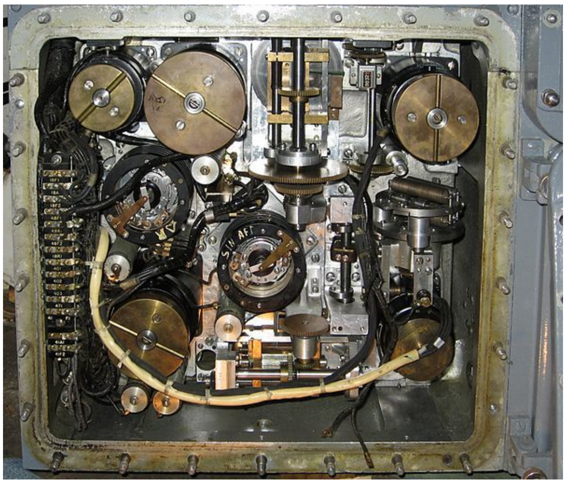
Determining the gyro angle required the real-time solution of a complex trigonometric equation (see Equation 1 for a simplified example). The TDC provided a continuous solution to this equation using data updates from the submarine’s navigation sensors and the TDC’s target tracker. The TDC was also able to automatically update all torpedo gyro angle settings simultaneously with a fire control solution, which improved the accuracy over systems that required manual updating of the torpedo’s course.[28]

The TDC enables the submarine to launch the torpedo on a course different from that of the submarine, which is important tactically. Otherwise the submarine would need to be pointed at the projected intercept point in order to launch a torpedo.[29] Requiring the entire vessel to be pointed in order to launch a torpedo would be time consuming, require precise submarine course control, and would needlessly complicate the torpedo firing process. The TDC with target tracking gives the submarine the ability to maneuver independently of the required target intercept course for the torpedo.

As is shown in Figure 2, in general, the torpedo does not actually move in a straight path immediately after launch and it does not instantly accelerate to full speed, which are referred to as torpedo ballistic characteristics. The ballistic characteristics are described by three parameters: reach, turning radius, and corrected torpedo speed. Also, the target bearing angle is different from the point of view of the periscope versus the point of view of the torpedo, which is referred to as torpedo tube parallax.[30] These factors are a significant complication in the calculation of the gyro angle and the TDC must compensate for their effects.

Straight running torpedoes were usually launched in salvo (i.e. multiple launches in a short period of time)[31] or a spread (i.e. multiple launches with slight angle offsets)[31] to increase the probability of striking the target given the inaccuracies present in the measurement of angles, target range, target speed, torpedo track angle, and torpedo speed.

Salvos and spreads were also launched to strike tough targets multiple times to ensure their destruction.[32] The TDC supported the firing of torpedo salvos by allowing short time offsets between firings and torpedo spreads by adding small angle offsets to each torpedo's gyro angle. Before the sinking of South Korea's ROKS *Cheonan* by North Korea in 2010, the last warship sunk by a submarine torpedo attack, the ARA *General Belgrano* in 1982, was struck by two torpedoes from a three torpedo spread.[33]



A look inside the TDC

To accurately compute the gyro angle for a torpedo in a general engagement scenario, the target course, range, and bearing must be accurately known. During World War II, target course, range, and bearing estimates often had to be generated using periscope observations, which were highly subjective and error prone. The TDC was used to refine the estimates of the target's course, range, and bearing through a process of

- estimating the target's course, speed, and range based on observations.
- using the TDC to predict the target's position at a future time based on the estimates of the target's course, speed, and range.
- comparing the predicted position against the actual position and correcting the estimated parameters as required to achieve agreement between the predictions and observation. Agreement between prediction and observation means that the target course, speed, and range estimates are accurate.

Estimating the target's course was generally considered the most difficult of the observation tasks. The accuracy of the result was highly dependent on the experience of the skipper. During combat, the actual course of the target was not usually determined but instead the skippers determined a related quantity called "angle on the bow." Angle on the bow is the angle formed by the target course and the line of sight to the submarine. Some skippers, like the legendary Richard O'Kane, practiced determining the angle on the bow by looking at IJN ship models mounted on a calibrated lazy Susan through an inverted binocular barrel.[34]

To generate target position data versus time, the TDC needed to solve the equations of motion for the target relative to the submarine. The equations of motion are differential equations and the TDC used mechanical integrators to generate its solution.[35]

The TDC needed to be positioned near other fire control equipment to minimize the amount of electromechanical interconnect. Because submarine space within the pressure hull was limited, the TDC needed to be as small as possible. On World War II submarines, the TDC and other fire control equipment was mounted in the conning tower, which was a very small space.[36] The packaging problem was severe and the performance of some early torpedo fire control equipment was hampered by the need to make it small.[37]

3.1.3 TDC functional description

Since the TDC actually performed two separate functions, generating target position estimates and computing torpedo firing angles, the TDC actually consisted of two types of analog computers:

- Angle solver: This computer calculates the required gyro angle. The TDC had separate angle solvers for the forward and aft torpedo tubes.
- Position keeper: This computer generates a continuously updated estimate of the target position based on earlier target position measurements.[38]

Angle solver

The equations implemented in the angle solver can be found in the Torpedo Data Computer manual.[39] The Submarine Torpedo Fire Control Manual[40] discusses the calculations in a general sense and a greatly abbreviated form of that discussion is presented here.

The general torpedo fire control problem is illustrated in Figure 2. The problem is made more tractable if we assume:

- The periscope is on the line formed by the torpedo running along its course
- The target moves on a fixed course and speed
- The torpedo moves on a fixed course and speed

As can be seen in Figure 2, these assumptions are not true in general because of the torpedo ballistic characteristics

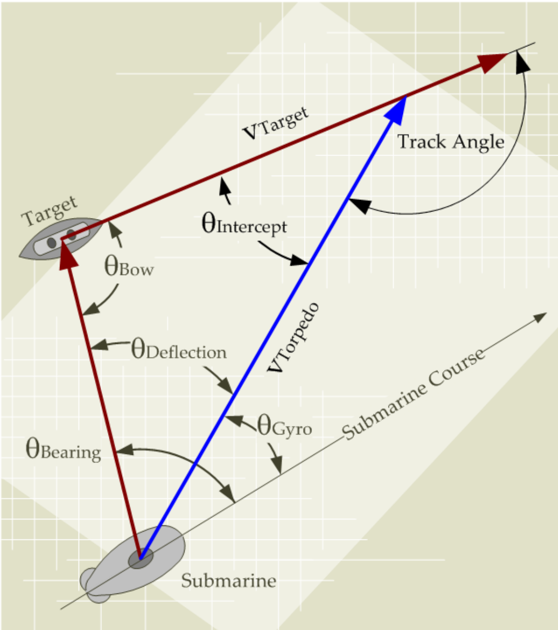


Figure 3: The torpedo fire control triangle

and torpedo tube parallax. Providing the details as to how to correct the torpedo gyro angle calculation for ballistics and parallax is complicated and beyond the scope of this article. Most discussions of gyro angle determination take the simpler approach of using Figure 3, which is called the torpedo fire control triangle.[8][9] Figure 3 provides an accurate model for computing the gyro angle when the gyro angle is small, usually less than 30°.[41]

The effects of parallax and ballistics are minimal for small gyro angle launches because the course deviations they cause are usually small enough to be ignorable. U.S. submarines during World War II preferred to fire their torpedoes at small gyro angles because the TDC's fire control solutions were most accurate for small angles.[42]

The problem of computing the gyro angle setting is a trigonometry problem that is simplified by first considering the calculation of the deflection angle, which ignores torpedo ballistics and parallax.[43] For small gyro angles, *θGyro ≈ θBearing - θDeflection*. A direct application of the law of sines to Figure 3 produces Equation 1.

(Equation 1)

$$\frac{\|v_{Target}\|}{\sin(\theta_{Deflection})} = \frac{\|v_{Torpedo}\|}{\sin(\theta_{Bow})}$$

where

vTarget is the velocity of the target.

vTorpedo is the velocity of the torpedo.

θBow is the angle of the target ship bow relative to the periscope line of sight.

θDeflection is the angle of the torpedo course relative to the periscope line of sight.

Range plays no role in Equation 1, which is true as long as the three assumptions are met. In fact, Equation 1 is the same equation solved by the mechanical sights of steerable torpedo tubes used on surface ships during World War I and World War II. Torpedo launches from steerable torpedo tubes meet the three stated assumptions well. However, an accurate torpedo launch from a submarine requires parallax and torpedo ballistic corrections when gyro angles are large. These corrections require knowing range accurately. When the target range was not known, torpedo launches requiring large gyro angles were not recommended.[44]

Equation 1 is frequently modified to substitute track angle for deflection angle (track angle is defined in Figure 2, *θTrack=θBow+θDeflection*). This modification is illustrated with Equation 2.

(Equation 2)

$$\frac{\|v_{Target}\|}{\sin(\theta_{Deflection})} = \frac{\|v_{Torpedo}\|}{\sin(\theta_{Track} - \theta_{Deflection})}$$

where

θTrack is the angle between the target ship's course and the torpedo's course.

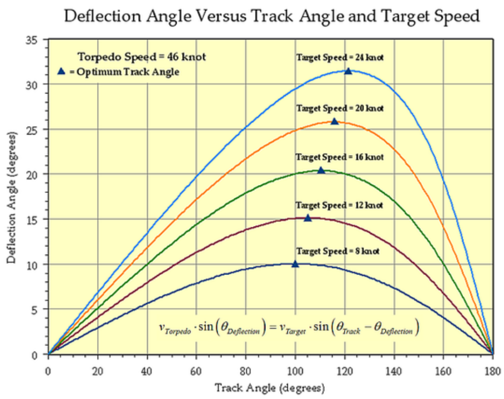


Figure 4: Deflection angle versus track angle and target speed ($\theta G_{yro} = 0^\circ$).

A number of publications[45][46] state the optimum torpedo track angle as 110° for a Mk 14 (46 knot weapon). Figure 4 shows a plot of the deflection angle versus track angle when the gyro angle is 0° (*i.e.*, *θDeflection=θBearing*).[47] Optimum track angle is defined as the point of minimum deflection angle sensitivity to track angle errors for a given target speed. This minimum occurs at the points of zero slope on the curves in Figure 4 (these points are marked by small triangles).

The curves show the solutions of Equation 2 for deflection angle as a function of target speed and track angle. Figure 4 confirms that 110° is the optimum track angle for a 16-knot (30 km/h) target, which would be a common ship speed.[48]

There is fairly complete documentation available for a Japanese torpedo fire control computer that goes through the details of correcting for the ballistic and parallax factors. While the TDC may not have used exactly the same approach, it was likely very similar.

Position keeper

As with the angle solver the equations implemented in the angle solver can be found in the Torpedo Data Computer manual.[39] Similar functions were implemented in the rangekeepers for surface ship-based fire control systems. For a general discussion of the principles behind the position keeper, see Rangekeeper.

3.2 Notes and references

[1] Friedman, Norman (1995). *US Submarines Through 1945: An Illustrated Design History*. Naval Institute Press. p. 195. ISBN 1-55750-263-3.

[2] “Analog Computers”. *Lexikon’s History of Computing*. 1995. Retrieved 2006-07-03.

[3] While the TDC’s target tracking abilities were unique for submarine torpedo fire control during WWII, target tracking was used on surface ship torpedo fire control systems by a number of nations (see references in this article to US destroyer and Japanese torpedo fire control). The TDC was the first analog computer to miniaturize the capability enough for deployment on a submarine.

[4] Beach, *Run Silent, Run Deep*

[5]

[6]

[7]

[8] O'Kane, Richard (1977). *Clear The Bridge:The War Patrols of the U.S.S. Tang*. New York: Bantam Books. ISBN 0-553-14516-9.

[9] O'Kane, Richard (1987). *Wahoo: The Patrols of America’s Most Famous World War II Submarine*. New York: Bantam Books. ISBN 0-553-28161-5.; Beach, Edward L., Jr., Captain, USN (rtd). *Run Silent, Run Deep*, *passim*; Beach, *Dust on the Sea*, *passim*; Grider, George. *War Fish*, *passim*; Blair, Clay, Jr. *Silent Victory* (New York: Bantam, 1976), *passim*.

[10] Dusty Dornin was widely agreed to be the best. Blair, p.357.

[11] Blair, p.357.

[12] “Museum documents an operating US, WW II built submarine in Taiwan.”. Retrieved 2008-07-13.

[13] There were other forms of torpedo guidance attempted throughout WWII. Notable are the Japanese human-guided *Kaiten* and German pattern running and acoustic homing types for attacking convoys. Today, most submarine-launched torpedoes are wire-guided with terminal homing.

[14] Frederick J Milford (October 1997). “Part Five: Post WW-II Submarine Launched/ Heavyweight Torpedoes”. *US Navy Torpedoes*. Archived from the original on 2006-05-23. Retrieved 2006-07-26.

[15] “Torpedo Data Computer”. *FleetSubmarine.com*. 2002. Retrieved 2006-07-03.

[16] Holwitt, Joel I. *“Execute Against Japan”*, Ph.D. dissertation, Ohio State University, 2005, p.147; Beach, Edward L., Jr. *Run Silent, Run Deep*.

[17] “Firing a Torpedo Using A Mechanical Computing Sight”. *The Dreadnought Project*. 2000. Retrieved 2006-07-11.

[18] Holwitt, p. 147.

[19]

[20] Britain

[21] Jackson, USNR, Lt.(jg) J.G. (February 1946). *Japanese Torpedo Fire Control* (PDF). US Naval Technical Mission to Japan. Fascicle O-1, Target O-32.

[22] Holwitt, p.147.

[23] Mohl, Michael (2006). “Tambor (SS-198)". *NavSource Online: Submarine Photo Archive*. Retrieved 2006-08-01.

[24] Beach, Edward L., Jr. *Dust on the Sea*.

[25] Holwitt, p.147; Friedman, Norman. *U.S. Submarines Through 1945* (Annapolis: U.S. Naval Institute Press, 1995), p.195.

[26] The Mark 18 was electric and therefore wakeless and difficult for surface forces to trace. On the downside, it was slower than the Mark 14. This made it more difficult to aim accurately because larger gyro angles were involved. Even so, thousands of them were fired during WWII.

[27] O'Kane, Richard (1977). *Clear The Bridge:The War Patrols of the U.S.S. Tang*. New York: Bantam Books. p. 221. ISBN= 0-553-14516-9.

[28] Friedman, Norman (1995). *US Submarines Through 1945: An Illustrated Design History*. Naval Institute Press. p. 196. ISBN 1-55750-263-3.

[29] Torpedoes were developed by the United States with this capability during WWI. However, without automated fire control it was difficult to realize the full advantages of this approach.

[30] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Definitions”. *Submarine Torpedo Fire Control Manual*. pp. 1–12. Retrieved 2006-08-22.

[31] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Definitions”. *Submarine Torpedo Fire Control Manual*. pp. 1–9. Retrieved 2006-08-22.

[32] Commander Submarine Force, Pacific Fleet, ed. (2006-02-17) [1944-02]. “Attacks -- General (Chapter IV, Section 1)". *Current Submarine Doctrine*. pp. paragraph 4614. Retrieved 2006-07-02.

[33] Nathan Decker (July 2005), *Submarines 1950-2000, a study in unused potential*, archived from the original on 2007-03-17, retrieved 2006-08-20

[34] O'Kane, RIchard H. (1989) [1987]. “Part 4: Chapter 1”. *Wahoo: The Patrols of America's Most Famous World War II Submarine* (Bantam ed.). New York: Bantam. pp. 108–109. ISBN 0-553-28161-5.

[35] Bromley, Allan (1990). “Analog Computing Devices”. *Computing Before Computers*. Retrieved 2006-07-22.

[36] Wise, Robert (Director-One scene shows how cramped a conning tower could be.) (1958). *Run Silent, Run Deep* (Film). Pacific Ocean.

[37] Friedman, Norman (1995). *US Submarines Through 1945: An Illustrated Design History*. Naval Institute Press. p. 350. ISBN 1-55750-263-3.

[38] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Chapter 4: The Torpedo Fire Control Party”. *Submarine Torpedo Fire Control Manual*. pp. 4–2. Retrieved 2006-08-22.

[39] Bureau of Ordnance, ed. (June 1944) [1944-06]. *Torpedo Data Compter Mk 3 Mods 5 to 12*.

[40] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. *Submarine Torpedo Fire Control Manual*. Retrieved 2006-08-22.

[41] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Theory of Approach and Attack”. *Submarine Torpedo Fire Control Manual*. pp. 8–8, 8–9. Retrieved 2006-08-19.

[42] Commander Submarine Force, Pacific Fleet, ed. (2006-02-17) [1944-02]. “Attacks -- General (Chapter IV, Section 1)". *Current Submarine Doctrine*. Department of the Navy. pp. paragraph 4509. USF 25(A). Retrieved 2006-08-19.

[43] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Definitions”. *Submarine Torpedo Fire Control Manual*. pp. 1–2. Retrieved 2006-08-19.

[44] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Chapter 8: Theory of Approach and Attack”. *Submarine Torpedo Fire Control Manual*. pp. 8–10. Retrieved 2006-08-21.

[45] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Chapter 8: Theory of Approach and Attack”. *Submarine Torpedo Fire Control Manual*. pp. 8–9. Retrieved 2006-08-19.

[46] O'Kane, Richard (1977). “Part V, Chapter 3”. *Clear The Bridge:The War Patrols of the U.S.S. Tang*. New York: Bantam Books. p. 303. ISBN 0-553-14516-9.

[47] Most work on computing intercept angles is done using track angle as a variable. This is because track angle is a strictly a function of the target's course and speed along with the torpedo's course and speed. It removes the complexities associated with parallax and torpedo ballistics.

[48] Commander Submarine Force, United States Atlantic Fleet, ed. (2006-04-16) [1950-02]. “Chapter 5: Duties of the Fire Control Party”. *Submarine Torpedo Fire Control Manual*. pp. 5–25. Retrieved 2006-08-19.

3.3 External links

- USS Pampanito: Article on the Pampanito's TDC.
- Torpedo Data Computer Mk IV
- A. Ben Clymer: *The mechanical analog Computers of Hannibal Ford and William Newell*, IEEE Annals of the history of computing
- US Torpedo History: Good description of operational use of the Mk 14, Mk 18, and Mk 23
- Original Manual for the *Torpedo Data Computer Mark 3*
- Discussion of the torpedo ballistic and parallax corrections used by the Imperial Japanese Navy

Chapter 4

Analog computer

A page from the Bombardier's Information File *(BIF) that describes the components and controls of the Norden bombsight. The* ***Norden bombsight*** *was a highly sophisticated optical/mechanical analog computer used by the United States Army Air Force during World War II, the Korean War, and the Vietnam War to aid the pilot of a bomber aircraft in dropping bombs accurately.*

An **analog computer** is a form of computer that uses the continuously changeable aspects of physical phenomena such as electrical, mechanical, or hydraulic quantities to model the problem being solved. In contrast, digital computers represent 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. Analog computers do not suffer from the quantization noise inherent in digital computers, but are limited instead by analog noise.

Analog computers were widely used in scientific and industrial applications where digital computers of the time lacked sufficient performance. Analog computers can have a very wide range of complexity. Slide rules and nomographs are the simplest, while naval gunfire control computers and large hybrid digital/analog computers were among the most complicated.[1] Systems for process control and protective relays used analog computation to perform control and protective functions.

The advent of digital computing and its success made analog computers largely obsolete in 1950s and 1960s, though they remain in use in some specific applications, like the flight computer in aircraft, and for teaching control systems in universities.

4.1 Setup

Setting up an analog computer required scale factors to be chosen, along with initial conditions—that is, starting values. Another essential was creating the required network of interconnections between computing elements. Sometimes it was necessary to re-think the structure of the problem so that the computer would function satisfactorily. No variables could be allowed to exceed the computer's limits, and differentiation was to be avoided, typically by rearranging the "network" of interconnects, using integrators in a different sense.

Running an electronic analog computer, assuming a satisfactory setup, started with the computer held with some variables fixed at their initial values. Moving a switch released the holds and permitted the problem to run. In some instances, the computer could, after a certain running time interval, repeatedly return to the initial-conditions state to reset the problem, and run it again.

4.2 Timeline of analog computers

4.2.1 Precursors

This is a list of examples of early computation devices which are considered to be precursors of the modern computers. Some of them may even have been dubbed as 'computers' by the press, although they may fail to fit the modern definitions.

The ancient Greek-designed Antikythera mechanism, dating between 150 to 100 BC, is the world's oldest known analog computer.

The Antikythera mechanism is believed to be the earliest mechanical analog "computer", according to Derek J. de Solla Price.[2] It was designed to calculate astronomical positions. It was discovered in 1901 in the Antikythera wreck off the Greek island of Antikythera, between Kythera and Crete, and has been dated to *circa* 100 BC. Devices of a level of complexity comparable to that of the Antikythera mechanism would not reappear until a thousand years later.

Many mechanical aids to calculation and measurement were constructed for astronomical and navigation use. The planisphere was a star chart invented by Abū Rayhān al-Bīrūnī in the early 11th century.[3] The astrolabe was invented in the Hellenistic world in either the 1st or 2nd centuries BC and is often attributed to Hipparchus. A combination of the planisphere and dioptra, the astrolabe was effectively an analog computer capable of working out several different kinds of problems in spherical astronomy. An astrolabe incorporating a mechanical calendar computer[4][5] and gear-wheels was invented by Abi Bakr of Isfahan, Persia in 1235.[6] Abū Rayhān al-Bīrūnī invented the first mechanical geared lunisolar calendar astrolabe,[7] an early fixed-wired knowledge processing machine[8] with a gear train and gear-wheels,[9] *circa* 1000 AD.

The sector, a calculating instrument used for solving problems in proportion, trigonometry, multiplication and division, and for various functions, such as squares and cube roots, was developed in the late 16th century and found application in gunnery, surveying and navigation.

The planimeter was a manual instrument to calculate the area of a closed figure by tracing over it with a mechanical linkage.

A slide rule

The slide rule was invented around 1620–1630, shortly after the publication of the concept of the logarithm. It is a hand-operated analog computer for doing multiplication and division. As slide rule development progressed, added scales provided reciprocals, squares and square roots, cubes and cube roots, as well as transcendental functions such as logarithms and exponentials, circular and hyperbolic trigonometry and other functions. Aviation is one of the few fields where slide rules are still in widespread use, particularly for solving time–distance problems in light aircraft.

The tide-predicting machine invented by Sir William Thomson in 1872 was of great utility to navigation in shallow waters. It used a system of pulleys and wires to automatically calculate predicted tide levels for a set period at a particular location.

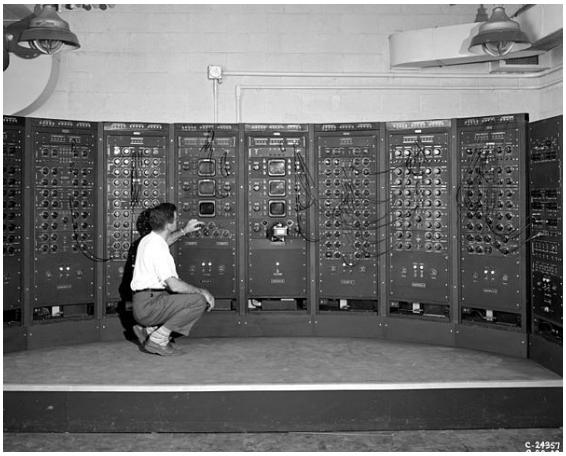
The differential analyser, a mechanical analog computer designed to solve differential equations by integration, used wheel-and-disc mechanisms to perform the integration. In 1876 Lord Kelvin had already discussed the possible construction of such calculators, but he had been stymied by the limited output torque of the ball-and-disk integrators.[10] In a differential analyzer, the output of one integrator drove the input of the next integrator, or a graphing output. The torque amplifier was the advance that allowed these machines to work. Starting in the 1920s, Vannevar Bush and others developed mechanical differential analyzers.

4.2.2 Modern era

The Dumaresq was a mechanical calculating device invented around 1902 by Lieutenant John Dumaresq of the Royal Navy. It was an analog computer which related vital variables of the fire control problem to the movement of one's own ship and that of a target ship. It was often used with other devices, such as a Vickers range clock to generate range and deflection data so the gun sights of the ship could be continuously set. A number of versions of the Dumaresq were produced of increasing complexity as development proceeded.

By 1912 Arthur Pollen had developed an electrically driven mechanical analog computer for fire-control systems, based on the differential analyser. It was used by the Imperial Russian Navy in World War I.

Starting in 1929, AC network analyzers were constructed to solve calculation problems related to electrical power



Analog computing machine at the Lewis Flight Propulsion Laboratory in 1949.

Heathkit EC-1 educational analog computer

systems that were too large to solve with numerical methods at the time.[11] These were essentially scale models of the electrical properties of the full-size system. Since network analyzers could handle problems too large for analytic methods or hand computation, they were also used to solve problems in nuclear physics and in the design of structures. More than 50 large network analyzers were built by the end of the 1950s.

World War II era gun directors, gun data computers, and bomb sights used mechanical analog computers. Mechanical analog computers were very important in gun fire control in World War II, The Korean War and well past the Vietnam War; they were made in significant numbers.

The FERMIAC was an analog computer invented by physicist Enrico Fermi in 1947 to aid in his studies of neutron transport.[12] Project Cyclone was an analog computer developed by Reeves in 1950 for the analysis and design of dynamic systems.[13] Project Typhoon was an analog computer developed by RCA in 1952. It consisted of over 4000 electron tubes and used 100 dials and 6000 plug-in connectors to program.[14] The MONIAC Computer was a hydraulic model of a national economy first unveiled in 1949.

Computer Engineering Associates was spun out of Caltech in 1950 to provide commercial services using the "Direct Analogy Electric Analog Computer" ("the largest and most impressive general-purpose analyzer facility for the solution of field problems") developed there by Gilbert D. McCann, Charles H. Wilts, and Bart Locanthi.[15][16]

Educational analog computers illustrated the principles of analog calculation. The Heathkit EC-1, a $199 educational analog computer was made by the Heath Company, USA c. 1960.[17] It was programmed using patch cords that connected nine operational amplifiers and other components.[18] General Electric also marketed an "educational" analog computer kit of a simple design in the early 1960s consisting of a two transistor tone generator and three potentiometers wired such that the frequency of the oscillator was nulled when the potentiometer dials were positioned by hand to satisfy an equation. The relative resistance of the potentiometer was then equivalent to the formula of the equation being solved. Multiplication or division could be performed depending on which dials were considered inputs and which was the output. Accuracy and resolution was limited and a simple slide rule was more accurate, however, the unit did demonstrate the basic principle.

In industrial process control, thousands of analog loop controllers were used to automatically regulate temperature, flow, pressure, or other process conditions. The technology of these controllers ranged from purely mechanical integrators, through vacuum-tube and solid-state devices, to emulation of analog controllers by microprocessors.

4.3 Electronic analog computers

The similarity between linear mechanical components, such as springs and dashpots (viscous-fluid dampers), and electrical components, such as capacitors, inductors, and resistors is striking in terms of mathematics. They can be modeled using equations of the same form.

However, the difference between these systems is what makes analog computing useful. If one considers a simple mass–spring system, constructing the physical system would require making or modifying the springs and masses. This would be followed by attaching them to each other and an appropriate anchor, collecting test equipment with the appropriate input range, and finally, taking measurements. In more complicated cases, such as suspensions for racing cars, experimental construction, modification, and testing is not so simple nor inexpensive.

The electrical equivalent can be constructed with a few operational amplifiers (op amps) and some passive linear components; all measurements can be taken directly with an oscilloscope. In the circuit, the (simulated) 'stiffness

Polish analog computer AKAT-1

of the spring', for instance, can be changed by adjusting the parameters of a capacitor. The electrical system is an analogy to the physical system, hence the name, but it is less expensive to construct, generally safer, and typically much easier to modify.

As well, an electronic circuit can typically operate at higher frequencies than the system being simulated. This allows the simulation to run faster than real time (which could, in some instances, be hours, weeks, or longer). Experienced users of electronic analog computers said that they offered a comparatively intimate control and understanding of the problem, relative to digital simulations.

The drawback of the mechanical-electrical analogy is that electronics are limited by the range over which the variables may vary. This is called dynamic range. They are also limited by noise levels. Floating-point digital calculations have comparatively huge dynamic range.

These electric circuits can also easily perform a wide variety of simulations. For example, voltage can simulate water pressure and electric current can simulate rate of flow in terms of cubic metres per second. An integrator can provide the total accumulated volume of liquid, using an input current proportional to the (possibly varying) flow rate.

Analog computers are especially well-suited to representing situations described by differential equations. Occasionally, they were used when a differential equation proved very difficult to solve by traditional means.

The accuracy of an analog computer is limited by its computing elements as well as quality of the internal power and electrical interconnections. The precision of the analog computer readout was limited chiefly by the precision of the readout equipment used, generally three or four significant figures. The precision of a digital computer is limited by the word size; arbitrary-precision arithmetic, while relatively slow, provides any practical degree of precision that might be needed.

Many small computers dedicated to specific computations are still part of industrial equipment's for regulation, but from years 1950 to 1980, general purpose analog computers were the only systems fast enough for real time simulation of dynamic systems, especially in the aircraft, military and aerospace field. In years 1970 every big company or administration highly concerned by dynamics problems had a big analog computing center :

USA: NASA (Huntsville, Houston), Martin Marietta (Orlando), Looked, Westinghouse, Hughes Aircraft, etc...

Europe: CEA (French Atomic Energy Commission), MATRA, Aerospatiale, BAC (British Aircraft Company),...

The major manufacturer was Electronic Associates (Long Branch USA). In years 1960 with its 231R Analog Computer (vacuum tubes, 20 Integrators) then with its 8800 Analog Computer (solid state op. amplifiers, 64 integrators). Its US challenger was Applied Dynamics (Ann Arbor, USA)

The basic technology for analog computers is “operational amplifiers” (also called “continuous current amplifiers” because they have no low frequency limitation) but in years 1960 an attempt was done to use alternative technology : medium frequency carrier and non dissipative reversible circuits(computer ANALAC France).

4.4 Analog–digital hybrid computers and hybrid computing devices

Analog computing devices are fast, digital computing devices are more versatile and accurate, so the idea is to combine the two processes for the best efficiency. An example of such hybrid elementary device is the hybrid multiplier where one input is an analog signal, the other input is a digital signal and the output is analog. It acts as an analog potentiometer upgradable digitally. Presently this kind of hybrid technique is mainly used for very fast dedicated real time computation when computing time is very critical as signal processing for radars and generally for controllers in embedded systems.

In the early 1970s analog computer manufacturers tried to tie together their analog computer with a digital computer to get the advantages of the two techniques . In such system, the digital computer will control the analog computer, providing initial set-up, initiating multiple analog runs, and automatically feeding and collecting data. The digital computer may also participate to the calculation itself using analog to digital and digital to analog converters.

The largest manufacturer of hybrid computers was Electronics Associates Inc.(EAI). Their hybrid computer model 8900 was made of a digital computer and one or more analog consoles. These systems were mainly dedicated to large projects such as the Apollo program and Space Shuttle at NASA,or Ariane in Europe. , especially during the integration step where at the beginning everything is simulated, and progressively real components replace their simulated part.

Only one company was known as offering general commercial computing services on its hybrid computers(CISI France ~1970 to 1980). The best reference in this field is the 100 000 simulations runs for each certification the automatic landing system of Airbus and Concord planes.

After 1980, purely digital computers progressed more and more rapidly and were fast enough to compete with analog computers. One key of the speed of analog computers was its full parallel computation, but this was also a limitation. The more equations required for a problem, the more analog physical operators are needed, even when the problem isn't time critical. “Programming” a problem consists of interconnecting the analog operators; even with a removable wiring panel it’s not versatile at all. So presently there are no more big hybrid computers, but only hybrid components, AD and DA converters to tie digital computers with the analog world.

4.5 Implementations

4.5.1 Mechanical analog computers

While a wide variety of mechanisms have been developed throughout history, some stand out because of their theoretical importance, or because they were manufactured in significant quantities.

Most practical mechanical analog computers of any significant complexity used rotating shafts to carry variables from one mechanism to another. Cables and pulleys were used in a Fourier synthesizer, a tide-predicting machine, which summed the individual harmonic components. Another category, not nearly as well known, used rotating shafts only for input and output, with precision racks and pinions. The racks were connected to linkages that performed the computation. At least one US Naval sonar fire control computer of the later 1950s, made by Librascope, was of this type, as was the principal computer in the Mk. 56 Gun Fire Control System.

Online, there is a remarkably clear illustrated reference (OP 1140) that describes[19] the fire control computer mechanisms. For adding and subtracting, precision miter-gear differentials were in common use in some computers; the Ford Instrument Mark I Fire Control Computer contained about 160 of them.

Integration with respect to another variable was done by a rotating disc driven by one variable. Output came from a pickoff device (such as a wheel) positioned at a radius on the disc proportional to the second variable. (A carrier with a pair of steel balls supported by small rollers worked especially well. A roller, its axis parallel to the disc’s surface, provided the output. It was held against the pair of balls by a spring.)

Arbitrary functions of one variable were provided by cams, with gearing to convert follower movement to shaft rotation.

Functions of two variables were provided by three-dimensional cams. In one good design, one of the variables rotated the cam. A hemispherical follower moved its carrier on a pivot axis parallel to that of the cam’s rotating axis. Pivoting motion was the output. The second variable moved the follower along the axis of the cam. One practical application was ballistics in gunnery.

Coordinate conversion from polar to rectangular was done by a mechanical resolver (called a “component solver” in US Navy fire control computers). Two discs on a common axis positioned a sliding block with pin (stubby shaft) on it. One disc was a face cam, and a follower on the block in the face cam’s groove set the radius. The other disc, closer to the pin, contained a straight slot in which the block moved. The input angle rotated the latter disc (the face cam disc, for an unchanging radius, rotated with the other (angle) disc; a differential and a few gears did this correction).

Referring to the mechanism’s frame, the location of the pin corresponded to the tip of the vector represented by the angle and magnitude inputs. Mounted on that pin was a square block.

Rectilinear-coordinate outputs (both sine and cosine, typically) came from two slotted plates, each slot fitting on the block just mentioned. The plates moved in straight lines, the movement of one plate at right angles to that of the other. The slots were at right angles to the direction of movement. Each plate, by itself, was like a Scotch yoke, known to steam engine enthusiasts.

During World War II, a similar mechanism converted rectilinear to polar coordinates, but it was not particularly successful and was eliminated in a significant redesign (USN, Mk. 1 to Mk. 1A).

Multiplication was done by mechanisms based on the geometry of similar right triangles. Using the trigonmetric terms for a right triangle, specifically opposite, adjacent, and hypotenuse, the adjacent side was fixed by construction. One variable changed the magnitude of the opposite side. In many cases, this variable changed sign; the hypotenuse could coincide with the adjacent side (a zero input), or move beyond the adjacent side, representing a sign change.

Typically, a pinion-operated rack moving parallel to the (trig.-defined) opposite side would position a slide with a slot coincident with the hypotenuse. A pivot on the rack let the slide's angle change freely. At the other end of the slide (the angle, in trig, terms), a block on a pin fixed to the frame defined the vertex between the hypotenuse and the adjacent side.

At any distance along the adjacent side, a line perpendicular to it intersects the hypotenuse at a particular point. The distance between that point and the adjacent side is some fraction that is the product of *1* the distance from the vertex, and *2* the magnitude of the opposite side.

The second input variable in this type of multiplier positions a slotted plate perpendicular to the adjacent side. That slot contains a block, and that block's position in its slot is determined by another block right next to it. The latter slides along the hypotenuse, so the two blocks are positioned at a distance from the (trig.) adjacent side by an amount proportional to the product.

To provide the product as an output, a third element, another slotted plate, also moves parallel to the (trig.) opposite side of the theoretical triangle. As usual, the slot is perpendicular to the direction of movement. A block in its slot, pivoted to the hypotenuse block positions it.

A special type of integrator, used at a point where only moderate accuracy was needed, was based on a steel ball, instead of a disc. It had two inputs, one to rotate the ball, and the other to define the angle of the ball's rotating axis. That axis was always in a plane that contained the axes of two movement-pickoff rollers, quite similar to the mechanism of a rolling-ball computer mouse (in this mechanism, the pickoff rollers were roughly the same diameter as the ball). The pickoff roller axes were at right angles.

A pair of rollers "above" and "below" the pickoff plane were mounted in rotating holders that were geared together. That gearing was driven by the angle input, and established the rotating axis of the ball. The other input rotated the "bottom" roller to make the ball rotate.

Essentially, the whole mechanism, called a component integrator, was a variable-speed drive with one motion input and two outputs, as well as an angle input. The angle input varied the ratio (and direction) of coupling between the "motion" input and the outputs according to the sine and cosine of the input angle.

Although they did not accomplish any computation, electromechanical position servos were essential in mechanical analog computers of the "rotating-shaft" type for providing operating torque to the inputs of subsequent computing mechanisms, as well as driving output data-transmission devices such as large torque-transmitter synchros in naval computers.

Other non-computational mechanisms included internal odometer-style counters with interpolating drum dials for indicating internal variables, and mechanical multi-turn limit stops.

Considering that accurately controlled rotational speed in analog fire-control computers was a basic element of their accuracy, there was a motor with its average speed controlled by a balance wheel, hairspring, jeweled-bearing differential, a twin-lobe cam, and spring-loaded contacts (ship's AC power frequency was not necessarily accurate, nor dependable enough, when these computers were designed).

4.5.2 Electronic analog computers

Electronic analog computers typically have front panels with numerous jacks (single-contact sockets) that permit patch cords (flexible wires with plugs at both ends) to create the interconnections which define the problem setup. In addition, there are precision high-resolution potentiometers (variable resistors) for setting up (and, when needed, varying) scale factors. In addition, there is likely to be a zero-center analog pointer-type meter for modest-accuracy voltage measurement. Stable, accurate voltage sources provide known magnitudes.

Typical electronic analog computers contain anywhere from a few to a hundred or more operational amplifiers ("op amps"), named because they perform mathematical operations. Op amps are a particular type of feedback amplifier with very high gain and stable input (low and stable offset). They are always used with precision feedback components that, in operation, all but cancel out the currents arriving from input components. The majority of op amps in a representative setup are summing amplifiers, which add and subtract analog voltages, providing the result at their output jacks. As well, op amps with capacitor feedback are usually included in a setup; they integrate the sum of their inputs with respect to time.

Integrating with respect to another variable is the nearly exclusive province of mechanical analog integrators; it is almost never done in electronic analog computers. However, given that a problem solution does not change with time, time can serve as one of the variables.

Other computing elements include analog multipliers, nonlinear function generators, and analog comparators.

Electrical elements such as inductors and capacitors used in electrical analog computers had to be carefully manufactured to reduce non-ideal effects. For example, in the construction of AC power network analyzers, one motive for using higher frequencies for the calculator (instead of the actual power frequency) was that higher-quality inductors could be more easily made. Many general-purpose analog computers avoided the use of inductors entirely, re-casting the problem in a form that could be solved using only resistive and capacitive elements, since high-quality capacitors are relatively easy to make.

The use of electrical properties in analog computers means that calculations are normally performed in real time (or faster), at a speed determined mostly by the frequency response of the operational amplifiers and other computing elements. In the history of electronic analog computers, there were some special high-speed types.

Nonlinear functions and calculations can be constructed to a limited precision (three or four digits) by designing function generators — special circuits of various combinations of resistors and diodes to provide the nonlinearity. Typically, as the input voltage increases, progressively more diodes conduct.

When compensated for temperature, the forward voltage drop of a transistor's base-emitter junction can provide a usably accurate logarithmic or exponential function. Op amps scale the output voltage so that it is usable with the rest of the computer.

Any physical process which models some computation can be interpreted as an analog computer. Some examples, invented for the purpose of illustrating the concept of analog computation, include using a bundle of spaghetti as a model of *sorting numbers*; a board, a set of nails, and a rubber band as a model of finding the *convex hull of a set of points*; and strings tied together as a model of *finding the shortest path in a network*. These are all described *in* A.K. Dewdney (see citation below).

4.6 Components

Analog computers often have a complicated framework, but they have, at their core, a set of key components which perform the calculations, which the operator manipulates through the computer's framework.

Key hydraulic components might include pipes, valves and containers.

Key mechanical components might include rotating shafts for carrying data within the computer, miter gear differentials, disc/ball/roller integrators, cams (2-D and 3-D), mechanical resolvers and multipliers, and torque servos.

Key electrical/electronic components might include:

- Precision resistors and capacitors
- operational amplifiers
- Multipliers
- potentiometers
- fixed-function generators

The core mathematical operations used in an electric analog computer are:

A 1960 Newmark analogue computer, made up of five units. This computer was used to solve differential equations and is currently housed at the Cambridge Museum of Technology.

- addition
- integration with respect to time
- inversion
- multiplication
- exponentiation
- logarithm
- division

In some analog computer designs, multiplication is much preferred to division. Division is carried out with a multiplier in the feedback path of an Operational Amplifier.

Differentiation with respect to time is not frequently used, and in practice is avoided by redefining the problem when possible. It corresponds in the frequency domain to a high-pass filter, which means that high-frequency noise is amplified; differentiation also risks instability.

4.7 Limitations

In general, analog computers are limited by non-ideal effects. An analog signal is composed of four basic components: DC and AC magnitudes, frequency, and phase. The real limits of range on these characteristics limit analog computers. Some of these limits include the operational amplifier offset, finite gain, and frequency response, noise floor, non-linearities, temperature coefficient, and parasitic effects within semiconductor devices. For commercially available electronic components, ranges of these aspects of input and output signals are always figures of merit.

4.8 Decline

In 1950's to 1970's, digital computers based on first vacuum tubes, transistors, integrated circuits and then micro-processors became more economical and precise. This led digital computers to largely replace analog computers. Even so, some research in analog computation is still being done. A few universities still use analog computers to teach control system theory. The American company Comdyna manufactures small analog computers.[20] At Indiana University Bloomington, Jonathan Mills has developed the Extended Analog Computer based on sampling voltages in a foam sheet. At the Harvard Robotics Laboratory, analog computation is a research topic. Lyric Semiconductor's error correction circuits use analog probabilistic signals. Slide rules are still popular among aircraft personnel.

4.9 Practical examples

These are examples of analog computers that have been constructed or practically used:

- Boeing B-29 Superfortress Central Fire Control System
- Deltar
- Kerrison Predictor
- Leonardo Torres y Quevedo's Analogue Calculating Machines based on "fusee sans fin"
- Librascope, aircraft weight and balance computer
- Mechanical computer
- Mechanical integrators, for example, the planimeter
- Nomogram
- Norden bombsight
- Rangekeeper and related fire control computers
- Scanimate
- Torpedo Data Computer
- Torquetum
- Water integrator

Analog (audio) synthesizers can also be viewed as a form of analog computer, and their technology was originally based in part on electronic analog computer technology. The ARP 2600's Ring Modulator was actually a moderate-accuracy analog multiplier.

The Simulation Council (or Simulations Council) was an association of analog computer users in USA. It is now known as The Society for Modeling and Simulation International. The Simulation Council newsletters from 1952 to 1963 are available online and show the concerns and technologies at the time, and the common use of analog computers for missilry.[21]

4.10 See also

- Signal (electrical engineering)
- Signal (computing)
- Differential equation
- Dynamical system
- Chaos theory
- Analogical models
- Field-programmable analog array
- Voskhod Spacecraft "Globus" IMP navigation instrument

4.11 Notes

[1] http://arstechnica.com/information-technology/2014/03/gears-of-war-when-mechanical-analog-computers-ruled-the-waves/

[2] *The Antikythera Mechanism Research Project*, The Antikythera Mechanism Research Project. Retrieved 1 July 2007.

[3] G. Wiet, V. Elisseeff, P. Wolff, J. Naudu (1975). *History of Mankind, Vol 3: The Great medieval Civilisations*, p. 649. George Allen & Unwin Ltd, UNESCO.

[4] Fuat Sezgin "Catalogue of the Exhibition of the Institute for the History of Arabic-Islamic Science (at the Johann Wolfgang Goethe University", Frankfurt, Germany) Frankfurt Book Fair 2004, p.35 & 38.

[5] François Charette, Archaeology: High tech from Ancient Greece, Nature 444, 551-552(30 November 2006), doi: 10.1038/444551a

[6] Silvio A. Bedini, Francis R. Maddison (1966). "Mechanical Universe: The Astrarium of Giovanni de' Dondi", *Transactions of the American Philosophical Society* **56** (5), p. 1-69.

[7] D. De S. Price (1984). "A History of Calculating Machines", *IEEE Micro* **4** (1), p. 22-52.

[8] Tuncer Őren (2001). "Advances in Computer and Information Sciences: From Abacus to Holonic Agents", *Turk J Elec Engin* **9** (1), p. 63-70 [64].

[9] Donald Routledge Hill (1985). "Al-Biruni's mechanical calendar", *Annals of Science* **42**, p. 139-163.

[10] Ray Girvan, "The revealed grace of the mechanism: computing after Babbage", *Scientific Computing World*, May/June 2003

[11] Thomas Parke Hughes *Networks of power: electrification in Western society, 1880-1930* JHU Press, 1993 ISBN 0-8018-4614-5 page 376

[12] Metropolis, N. "The Beginning of the Monte Carlo Method." Los Alamos Science, No. 15, p. 125

[13] Small, J. S. "The analogue alternative: The electronic analogue computer in Britain and the USA, 1930-1975" Psychology Press, 2001, p. 90

[14] Small, J. S. "The analogue alternative: The electronic analogue computer in Britain and the USA, 1930-1975" Psychology Press, 2001, p. 93

[15] Howell N. Tyson Jr., "Caltech's Role in NASTRAN"

[16] *Analog Simulation: Solution of Field Problems*

[17] Petersen, Julie K. (2003). *Fiber optics illustrated dictionary*. CRC Press. p. 441. ISBN 0-8493-1349-X.

[18] "Heathkit EC - 1 Educational Analog Computer". Computer History Museum. Archived from the original on 20 May 2010. Retrieved 9 May 2010.

[19] World War II mechanical analog fire control computer mechanisms

[20] Comdyna home page retrieved 2011 Nov 18

[21] Simulation Council newsletter

4.12 References

- A.K. Dewdney. "On the Spaghetti Computer and Other Analog Gadgets for Problem Solving", *Scientific American*, 250(6):19-26, June 1984. Reprinted in *The Armchair Universe*, by A.K. Dewdney, published by W.H. Freeman & Company (1988), ISBN 0-7167-1939-8.
- Universiteit van Amsterdam Computer Museum. (2007). *Analog Computers*.
- Jackson, Albert S., "Analog Computation". London & New York: McGraw-Hill, 1960. OCLC 230146450

4.13 External links

- Biruni's eight-geared lunisolar calendar in Archaeology: High tech from Ancient Greece, François Charette, Nature 444, 551-552(30 November 2006), doi:10.1038/444551a
- The first computers
- Large collection of electronic analog computers with lots of pictures and documentation
- Large collection of old analog and digital computers at Old Computer Museum
- A great disappearing act: the electronic analogue computer Chris Bissell, The Open University, Milton Keynes, UK Accessed February 2007
- German computer museum with still runnable analog computers
- Analog computer basics
- Analog computer trumps Turing model
- Jonathan W. Mills's Analog Notebook
- Harvard Robotics Laboratory Analog Computation
- The Enns Power Network Computer – an analog computer for the analysis of electric power systems (advertisement from 1955)
- Librascope Development Company – Type LC-1 WWII Navy PV-1 "Balance Computor"

Chapter 5

Deltar

The Deltar (27 January 1972)

Layout of the Deltar. 1. Analog river sections 2. Peripheral equipment (Punched tape) 3. Operator controls 4. Measuring controls 5. Analog output (recorders) 6. Digital output (punched tape) 7. Design table (configuration of river setup) 8. Wind generator.

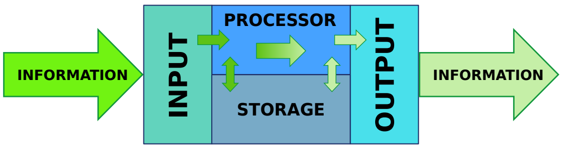
The **Deltar** (Delta Getij Analogon Rekenmachine, Dutch for Delta Tide Analog Calculator) was an analog computer, used from 1960 until 1984 in the design and implementation of the Delta Works.

The computer was designed and built in order to make the complicated calculations required to predict the effects of dams, dikes, and storm surge barriers on the tides in the estuaries of the rivers Rhine, Meuse and Scheldt.

The design of the Deltar was based on the analogy that exists between the properties and behaviour of water and electricity. Working with analogs of quantities such as water's height, rate of flow, and water storage, the design for the calculator basically used the electrical quantities charge, potential, inductance and capacitance.

Chapter 6

History of computing hardware



Computing hardware is a platform for information processing.

The Ishango bone

The **history of computing hardware** covers the developments from early simple devices to aid calculation to modern day computers.

Before the 20th century, most calculations were done by humans. Early mechanical tools to help humans with digital calculations were called "calculating machines", by proprietary names, or even as they are now, calculators. The machine operator was called the computer.

The first aids to computation were purely mechanical devices which required the operator to set up the initial values of an elementary arithmetic operation, then manipulate the device to obtain the result. Later, computers represented numbers in a continuous form, for instance distance along a scale, rotation of a shaft, or a voltage. Numbers could also be represented in the form of digits, automatically manipulated by a mechanical mechanism. Although this approach generally required more complex mechanisms, it greatly increased the precision of results. The invention of transistor and then integrated circuits made a breakthrough in computers. As a result digital computers largely replaced analog computers. The price of computers gradually became so low that first the personal computers and later mobile computers (smartphones and tablets) became ubiquitous.

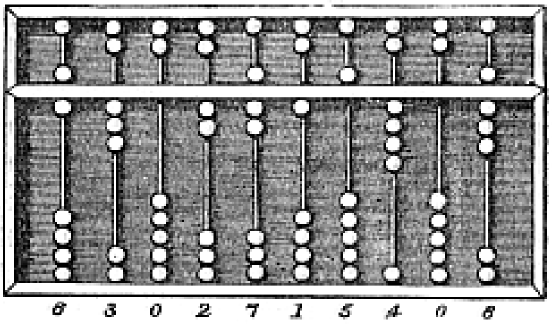
6.1 Early devices

6.1.1 Ancient era

Devices have been used to aid computation for thousands of years, mostly using one-to-one correspondence with fingers. The earliest counting device was probably a form of tally stick. Later record keeping aids throughout the Fertile Crescent included calculi (clay spheres, cones, etc.) which represented counts of items, probably livestock or grains, sealed in hollow unbaked clay containers.[1][2] The use of counting rods is one example.

The abacus was early used for arithmetic tasks. What we now call the Roman abacus was used in Babylonia as early as 2400 BC. Since then, many other forms of reckoning boards or tables have been invented. In a medieval European counting house, a checkered cloth would be placed on a table, and markers moved around on it according to certain rules, as an aid to calculating sums of money.

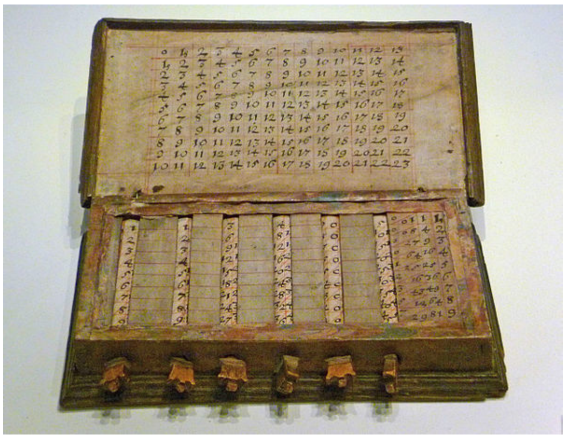
Several analog computers were constructed in ancient and medieval times to perform astronomical calculations. These include the Antikythera mechanism and the



Suanpan (the number represented on this abacus is 6,302,715,408)

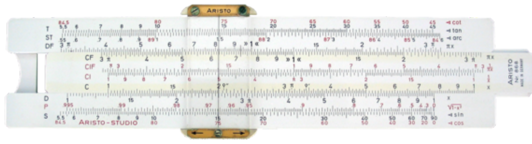
astrolabe from ancient Greece (c. 150–100 BC), which are generally regarded as the earliest known mechanical analog computers.[3] Hero of Alexandria (c. 10–70 AD) made many complex mechanical devices including automata and a programmable cart.[4] Other early versions of mechanical devices used to perform one or another type of calculations include the planisphere and other mechanical computing devices invented by Abu Rayhan al-Biruni (c. AD 1000); the equatorium and universal latitude-independent astrolabe by Abu Ishaq Ibrahim al-Zarqali (c. AD 1015); the astronomical analog computers of other medieval Muslim astronomers and engineers; and the astronomical clock tower of Su Song (c. AD 1090) during the Song Dynasty.

6.1.2 Medieval calculating tools



A set of John Napier's calculating tables from around 1680.

Scottish mathematician and physicist John Napier discovered that the multiplication and division of numbers could be performed by the addition and subtraction, respectively, of the logarithms of those numbers. While producing the first logarithmic tables, Napier needed to perform many tedious multiplications. It was at this point that he designed his 'Napier's bones', an abacus-like device that greatly simplified calculations that involved multiplication and division.[5]

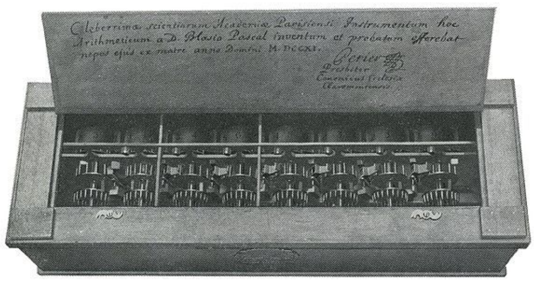


A slide rule

Since real numbers can be represented as distances or intervals on a line, the slide rule was invented in the 1620s, shortly after Napier's work, to allow multiplication and division operations to be carried out significantly faster than was previously possible.[6] Edmund Gunter built a calculating device with a single logarithmic scale at the University of Oxford. His device greatly simplified arithmetic calculations, including multiplication and division. William Oughtred greatly improved this in 1630 with his circular slide rule. He followed this up with the modern slide rule in 1632, essentially a combination of two Gunter rules, held together with the hands. Slide rules were used by generations of engineers and other mathematically involved professional workers, until the invention of the pocket calculator.[7]

6.1.3 Mechanical calculators

Wilhelm Schickard, a German polymath, designed a calculating machine in 1623 which combined a mechanised form of Napier's rods with the world's first mechanical adding machine built into the base. Because it made use of a single-tooth gear there were circumstances in which its carry mechanism would jam.[8] A fire destroyed at least one of the machines in 1624 and it is believed Schickard was too disheartened to build another.



View through the back of Pascal's calculator. Pascal invented his machine in 1642.

In 1642, while still a teenager, Blaise Pascal started some pioneering work on calculating machines and after three years of effort and 50 prototypes[9] he invented a mechanical calculator.[10][11] He built twenty of these machines (called Pascal's Calculator or Pascaline) in the following ten years.[12] Nine Pascalines have survived, most of which are on display in European museums.[13] A continuing debate exists over whether Schickard or Pascal should be regarded as the "inventor of the mechanical calculator" and the range of issues to be considered is discussed elsewhere.[14]

Gottfried Wilhelm von Leibniz invented the Stepped Reckoner and his famous stepped drum mechanism around 1672. He attempted to create a machine that could be used not only for addition and subtraction but would utilise a moveable carriage to enable long multiplication and division. Leibniz once said "It is unworthy of excellent men to lose hours like slaves in the labour of calculation which could safely be relegated to anyone else if machines were used."[15] However, Leibniz did not incorporate a fully successful carry mechanism. Leibniz also described the binary numeral system,[16] a central ingredient of all modern computers. However, up to the 1940s, many subsequent designs (including Charles Babbage's machines of the 1822 and even ENIAC of 1945) were based on the decimal system.[17]

Around 1820, Charles Xavier Thomas de Colmar created what would over the rest of the century become the first successful, mass-produced mechanical calculator, the Thomas Arithmometer. It could be used to add and subtract, and with a moveable carriage the operator could also multiply, and divide by a process of long multiplication and long division.[18] It utilised a stepped drum similar in conception to that invented by Leibniz. Mechanical calculators remained in use until the 1970s.

6.1.4 Punched card data processing

In 1801, Joseph-Marie Jacquard developed a loom in which the pattern being woven was controlled by punched cards. The series of cards could be changed without changing the mechanical design of the loom. This was a landmark achievement in programmability. His machine was an improvement over similar weaving looms. Punch cards were preceded by punch bands, as in the machine proposed by Basile Bouchon. These bands would inspire information recording for automatic pianos and more recently numerical control machine tools.

In the late 1880s, the American Herman Hollerith invented data storage on punched cards that could then be read by a machine.[19] To process these punched cards he invented the tabulator, and the key punch machine. His machines used mechanical relays (and solenoids) to increment mechanical counters. Hollerith's method was used in the 1890 United States Census and the completed results were "... finished months ahead of schedule and far under budget".[20] Indeed, the census was processed years faster than the prior census had been. Hollerith's company eventually became the core of IBM.

By 1920, electro-mechanical tabulating machines could add, subtract and print accumulated totals.[21] Machines were programmed by inserting dozens of wire jumpers into removable control panels. When the United States instituted Social Security in 1935, IBM punched card systems were used to process records of 26 million workers.[22] Punch cards became ubiquitous in industry and government for accounting and administration.

IBM punched card Accounting Machines, pictured in 1936.

Leslie Comrie's articles on punched card methods and W.J. Eckert's publication of *Punched Card Methods in Scientific Computation* in 1940, described punch card techniques sufficiently advanced to solve some differential equations[23] or perform multiplication and division using floating point representations, all on punched cards and unit record machines. Such machines were used during World War II for cryptographic statistical processing, as well as a vast number of administrative uses. The Astronomical Computing Bureau, Columbia University performed astronomical calculations representing the state of the art in computing.[24][25]

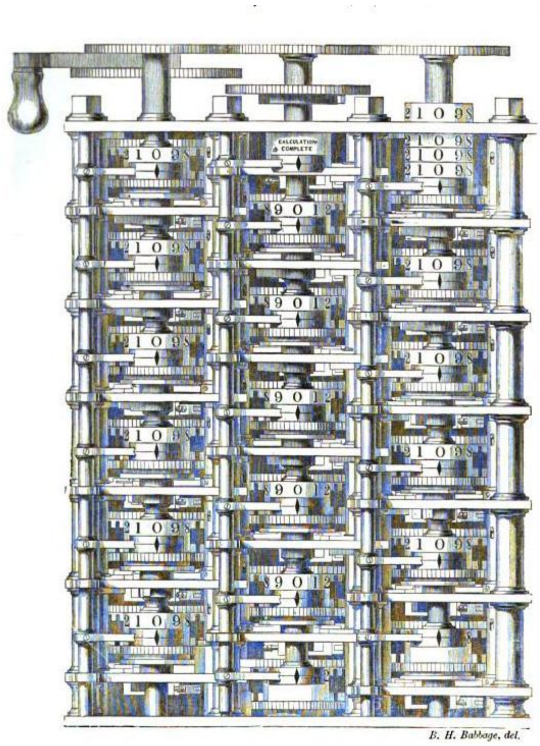
6.1.5 Calculators

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 people who used these calculators to perform mathematical calculations. 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.[26]

Companies like Friden, Marchant Calculator and Monroe made desktop mechanical calculators from the 1930s that

The Curta calculator could also do multiplication and division.



A portion of Babbage's Difference engine.

could add, subtract, multiply and divide.[27] 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's Arithmometer.

The world's first *all-electronic desktop* calculator was the British Bell Punch ANITA, released in 1961.[28][29] 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).

6.2 First general-purpose computing device

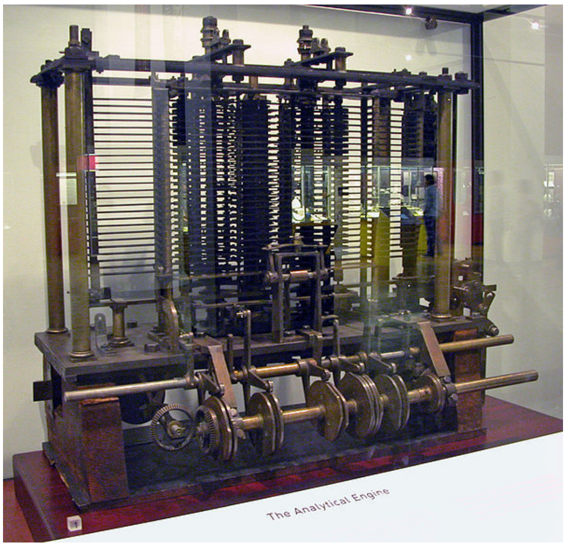
Main article: Analytical Engine

Charles Babbage, an English mechanical engineer and polymath, originated the concept of a programmable computer. Considered the "father of the computer",[30] he conceptualized and invented the first mechanical computer in the early 19th century. After working on his revolutionary difference engine, designed to aid in navigational calculations, in 1833 he realized that a much more general design, an Analytical Engine, was possible. The input of programs and data was to be provided to the machine via punched cards, a method being used at the time to direct mechanical looms such as the Jacquard loom. For output, the machine would have a printer, a curve plotter and a bell. The machine would also be able to punch numbers onto cards to be read in later. It employed ordinary base-10 fixed-point arithmetic.

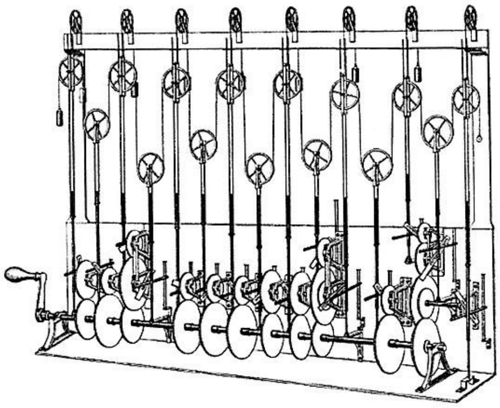
The Engine incorporated an arithmetic logic unit, control flow in the form of conditional branching and loops, and integrated memory, making it the first design for a general-purpose computer that could be described in modern terms as Turing-complete.[31][32]

There was to be a store, or memory, capable of holding 1,000 numbers of 40 decimal digits each (ca. 16.7 kB). An arithmetical unit, called the "mill", would be able to perform all four arithmetic operations, plus comparisons and optionally square roots. Initially it was conceived as a difference engine curved back upon itself, in a generally circular layout,[33] with the long store exiting off to one side. (Later drawings depict a regularized grid layout.)[34] Like the central processing unit (CPU) in a modern computer, the mill would rely upon its own internal procedures, roughly equivalent to microcode in modern CPUs, to be stored in the form of pegs inserted into rotating drums called "barrels", to carry out some of the more complex instructions the user's program might specify.[35]

The programming language to be employed by users was akin to modern day assembly languages. Loops and conditional branching were possible, and so the language as conceived would have been Turing-complete as later de-



Reconstruction of Babbage's Analytical Engine, the first general-purpose programmable computer.



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

fined by Alan Turing. Three different types of punch cards were used: one for arithmetical operations, one for numerical constants, and one for load and store operations, transferring numbers from the store to the arithmetical unit or back. There were three separate readers for the three types of cards.

The machine was about a century ahead of its time. However, the project was slowed by various problems including disputes with the chief machinist building parts for it. All the parts for his machine had to be made by hand - this was a major problem for a machine with thousands of parts. Eventually, the project was dissolved with the decision of the British Government to cease funding. Babbage's failure to complete the analytical engine can be chiefly attributed to difficulties not only of politics and financing, but also to his desire to develop an increasingly sophisticated computer and to move ahead faster than anyone else could follow. Ada Lovelace, Lord Byron's daughter, translated and added notes to the "*Sketch of the Analytical Engine*" by Federico Luigi, Conte Menabrea. This appears to be the first published description of programming.[36]

Following Babbage, although unaware of his earlier work, was Percy Ludgate, an accountant from Dublin, Ireland. He independently designed a programmable mechanical computer, which he described in a work that was published in 1909.

6.3 Analog computers

Main article: Analog 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.[37]

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.[38]

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.[39] In a differential analyzer, the output of one integrator drove the input of the next integrator, or a graphing output.

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;

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.

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).[40] It was used by the Imperial Russian Navy in World War I. 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[41] (United States Army Air Forces).

The art of mechanical analog computing reached its zenith with the differential analyzer,[42] 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.

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.

6.4 Advent of the digital computer

The principle of the modern computer was first described by computer scientist Alan Turing, who set out the idea in his seminal 1936 paper,[43] *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.

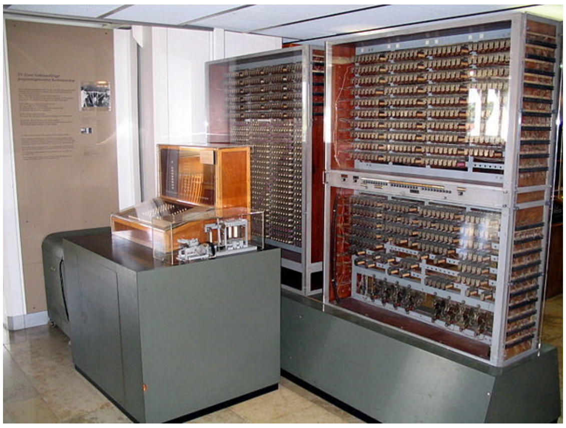
He also introduced the notion of a 'Universal Machine' (now known as a Universal Turing machine), with the idea that such a machine could perform the tasks of any other machine, or in other words, it is provably capable of computing anything that is computable by executing a program stored on tape, allowing the machine to be programmable. Von Neumann acknowledged that the central concept of the modern computer was due to this paper.[44] 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.

6.4.1 Electromechanical 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 electromechanical - electric switches drove mechanical relays to perform the calculation. These devices had a low operating speed and were eventually superseded by much faster all-electric computers, originally using vacuum tubes.

The Z2 was one of the earliest examples of an electromechanical relay computer, and was created by German engineer Konrad Zuse in 1939. It was an improvement on his earlier Z1; although it used the same mechanical memory, it replaced the arithmetic and control logic with electrical relay circuits.[45]

In the same year, the electro-mechanical bombes were built by British cryptologists to help decipher German Enigma-machine-encrypted secret messages during World War II. The initial design of the bombe was produced in 1939 at the UK Government Code and Cypher School (GC&CS) at Bletchley Park by Alan Turing,[46] with an important refinement devised in 1940 by Gordon Welchman.[47] The engineering design and construction was the work of Harold Keen of the British Tab-



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

ulating 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"*).

In 1941, Zuse followed his earlier machine up with the Z3,[48] the world's first working electromechanical programmable, fully automatic digital computer.[49] The Z3 was built with 2000 relays, implementing a 22 bit word length that operated at a clock frequency of about 5–10 Hz.[50] 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.[51] The Z3 was probably a complete Turing machine. 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 the British SSEM of 1948.[52]

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.

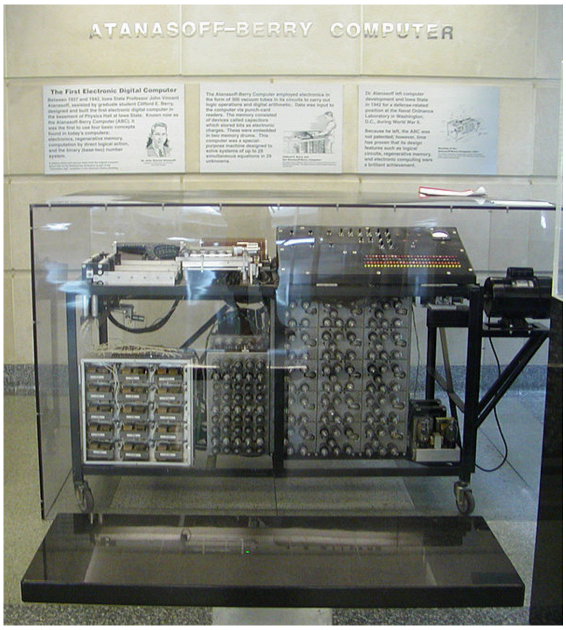
In 1944, the Harvard Mark I was constructed at IBM's Endicott laboratories;[53] it was a similar general purpose electro-mechanical computer to the Z3 and was not quite Turing-complete.

6.4.2 Digital computation

The mathematical basis of digital computing was established 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.[54]

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.[55] They showed[56] that electronic relays and switches can realize the expressions of Boolean algebra. This thesis essentially founded practical digital circuit design.

6.4.3 Electronic data processing



Atanasoff–Berry Computer replica at 1st floor of Durham Center, Iowa State University.

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.

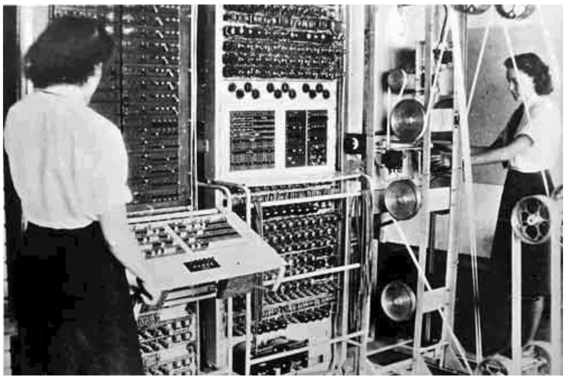
The engineer Tommy Flowers joined the telecommunications branch of the General Post Office in 1926. While working at the research station in Dollis Hill in the 1930s, he began to explore the possible use of electronics for the telephone exchange. Experimental equipment that he built in 1934 went into operation 5 years later, converting a portion of the telephone exchange network into an electronic data processing system, using thousands of vacuum tubes.[38]

In the US, John Vincent Atanasoff and Clifford E. Berry of Iowa State University developed and tested the Atanasoff–Berry Computer (ABC) in 1942,[57] the first electronic digital calculating device.[58] This design was also all-electronic, 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 work on the machine was discontinued. The machine's special-purpose nature and lack of a changeable, stored program distinguish it from modern computers.[59]

6.4.4 The electronic programmable computer

Main articles: Colossus computer and ENIAC

During World War II, the British at Bletchley Park

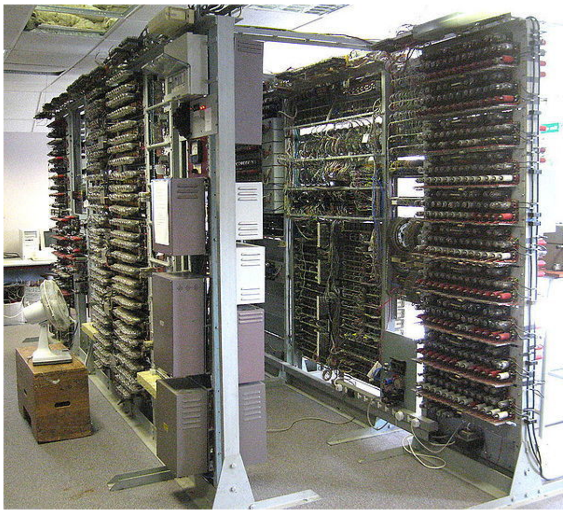


Colossus was the first electronic digital programmable computing device, and was used to break German ciphers during World War II.

(40 miles north of London) achieved a number of successes at breaking encrypted German military communications. The German encryption machine, Enigma, was first attacked with the help of the electro-mechanical bombes.[60] 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, termed "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 helped specify the Colossus.[61]

Tommy Flowers, still a senior engineer at the Post Office Research Station[62] was recommended to Max Newman by Alan Turing[63] and spent eleven months from early February 1943 designing and building the first Colossus.[64][65] After a functional test in December 1943, Colossus was shipped to Bletchley Park, where it was delivered on 18 January 1944[66] and attacked its first message on 5 February.[59]

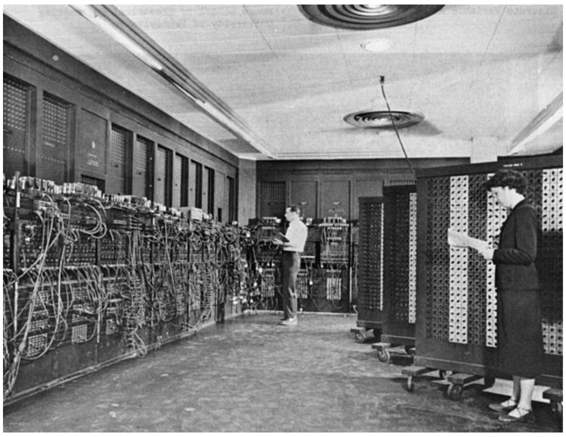


Colossus rebuild seen from the rear.

Colossus was the world's first electronic digital programmable computer.[38] 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, but it was not Turing-complete. Nine Mk II Colossi were built (The Mk I was converted to a Mk II making ten machines in total). Colossus Mark I contained 1500 thermionic valves (tubes), but Mark II with 2400 valves, 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.[67]

Colossus was able to process 5,000 characters per second with the paper tape moving at 40 ft/s (12.2 m/s; 27.3 mph). Sometimes, two or more Colossus computers tried different possibilities simultaneously in what now is called parallel computing, speeding the decoding process by perhaps as much as double the rate of comparison.

Colossus included the first ever use of shift registers and systolic arrays, enabling five simultaneous tests, each involving up to 100 Boolean calculations, on each of the five channels on the punched tape (although in normal operation only one or two channels were examined in any run). Initially Colossus was only used to determine the initial wheel positions used for a particular message (termed wheel setting). The Mark 2 included mechanisms intended to help determine pin patterns (wheel breaking). Both models were programmable using switches and plug panels in a way the Robinsons had not been.



ENIAC was the first Turing-complete electronic device, and performed ballistics trajectory calculations for the United States Army.[68]

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 encrypted 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.[69] A reconstructed working copy of one of the Colossus machines is now on display at Bletchley Park.

The US-built ENIAC (Electronic Numerical Integrator and Computer) was the first electronic programmable computer built in the US. Although the ENIAC was similar to the Colossus it was much faster and more flexible. It was unambiguously a Turing-complete device and could compute any problem that would fit into its memory. Like the Colossus, 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 written, it had to be mechanically set into the machine with manual resetting of plugs and switches.

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 (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.[70] 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.

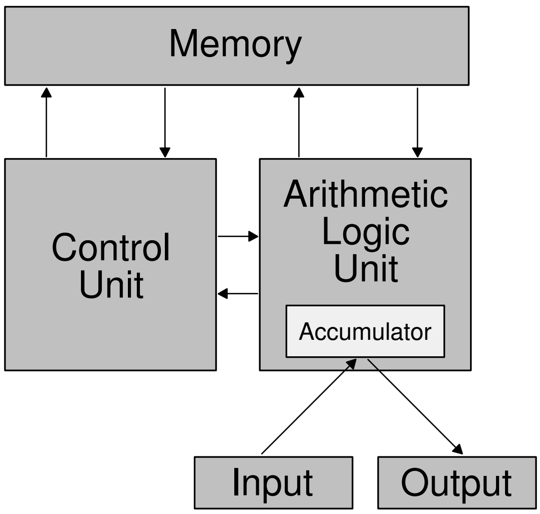
6.5 The stored-program computer

Further information: List of vacuum tube computers

Early computing machines had fixed programs. For example, a desk calculator is a fixed program computer. It can do basic mathematics, but it cannot be used as a word processor or a gaming console. Changing the program of a fixed-program machine requires re-wiring, re-structuring, or re-designing the machine. The earliest computers were not so much "programmed" as they were "designed". "Reprogramming", when it was possible at all, was a laborious process, starting with flowcharts and paper notes, followed by detailed engineering designs, and then the often-arduous process of physically re-wiring and re-building the machine.[71]

With the proposal of the stored-program computer this changed. A stored-program computer includes by design an instruction set and can store in memory a set of instructions (a program) that details the computation.

6.5.1 Theory



Design of the von Neumann architecture (1947)

The theoretical basis for the stored-program computer had been laid by Alan Turing in his 1936 paper. In 1945 Turing joined the National Physical Laboratory and began work on developing an electronic stored-program digital computer. His 1945 report 'Proposed Electronic Calculator' was the first specification for such a device.

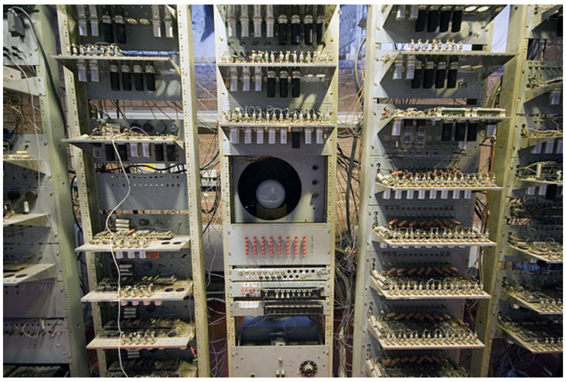
Meanwhile, John von Neumann at the Moore School of Electrical Engineering, University of Pennsylvania, circulated his *First Draft of a Report on the EDVAC* in 1945. Although substantially similar to Turing's design and containing comparatively little engineering detail, the computer architecture it outlined became known as the "von Neumann architecture". Turing presented a more detailed paper to the National Physical Laboratory (NPL) Executive Committee in 1946, giving the first reasonably complete design of a stored-program computer, a device he called the Automatic Computing Engine (ACE). However, the better-known EDVAC design of John von Neumann, who knew of Turing's theoretical work, received more publicity, despite its incomplete nature and questionable lack of attribution of the sources of some of the ideas.[38]

Turing felt that speed and size of memory were crucial and 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.

6.5.2 Manchester "baby"

Main article: Manchester Small-Scale Experimental Machine

The Manchester Small-Scale Experimental Machine,



A section of the Manchester Small-Scale Experimental Machine, the first stored-program computer

nicknamed *Baby*, was the world's first 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.[72]

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.[73] Invented by Freddie Williams and Tom Kilburn[74][75] 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.

Although the computer was considered "small and primitive" by the standards of its time, it was the first working machine to contain all of the elements essential to a modern electronic computer.[76] As soon as the SSEM had demonstrated the feasibility of its design, a project was initiated at the university to develop it 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.[77]

The SSEM 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^{18} (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^{18} - 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 SSEM had performed 3.5 million operations (for an effective CPU speed of 1.1 kIPS).

6.5.3 Manchester Mark 1

The Experimental machine led on to the development of the Manchester Mark 1 at the University of Manchester.[78] 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.

6.5.4 EDSAC

The other contender for being the first recognizably modern digital stored-program computer[79] was the EDSAC,[80] 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 computer.[81]

EDSAC ran its first programs on 6 May 1949, when it calculated a table of squares[82] 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 and was finally shut down on 11 July 1958, having been superseded by EDSAC 2 which stayed in use until 1965.[83]

6.5.5 EDVAC

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 would implement a number of important architectural and logical improvements conceived during the ENIAC's construction and would incorporate a high speed serial access memory.[84] 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.

6.5.6 Commercial computers

The first commercial 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).[85] 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.[86]

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 became operational in April 1951[87] 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 (Lyons Electronic Office). This was the first business application to go live on a stored program computer.[88]

Front panel of the IBM 650.

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 ($9.09 million as of 2015).[89] 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 11decimal digits plus sign (72-bit words).

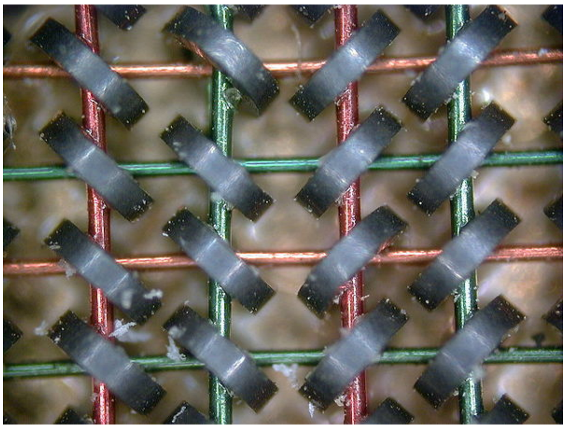
IBM introduced a smaller, more affordable computer in 1954 that proved very popular.[90] The IBM 650 weighed over 900 kg, the attached power supply weighed around 1350 kg and both were held in separate cabinets of roughly 1.5 meters by 0.9 meters by 1.8 meters. It cost US$500,000[91] ($4.39 million as of 2015) or could be leased for US$3,500 a month ($30 thousand as of 2015).[89] 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,[92] 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 not required.

6.5.7 Microprogramming

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 specialised 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).[93] 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.

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,[94] which also used multiple identical "bit slices" to simplify design. Interchangeable, replaceable tube assemblies were used for each bit of the processor.[95]

6.5.8 Magnetic storage



Magnetic core memory. Each core is one bit.

By 1954, magnetic core memory was rapidly displacing most other forms of temporary storage, including the Williams tube. It went on to dominate the field through the mid-1970s.[96]

A key feature of the American UNIVAC I system of 1951 was the implementation of a newly invented type of metal magnetic tape, and a high-speed tape unit, for non-volatile storage. Magnetic tape is still used in many computers.[97] In 1952, IBM publicly announced the IBM 701 Electronic Data Processing Machine, the first in its successful 700/7000 series and its first IBM mainframe computer. The IBM 704, introduced in 1954, used magnetic core memory, which became the standard for large machines.

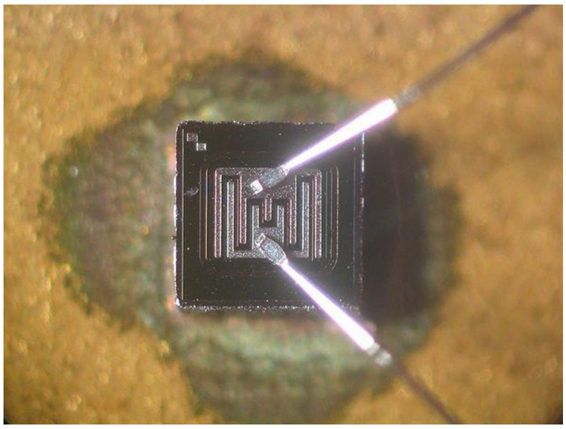
IBM introduced the first disk storage unit, the IBM 350 RAMAC (Random Access Method of Accounting and Control) in 1956. Using fifty 24-inch (610 mm) metal disks, with 100 tracks per side, it was able to store 5 megabytes of data at a cost of US$10,000 per megabyte ($90 thousand as of 2015).[89][98]

6.6 Early computer characteristics

6.7 Transistor computers

Main article: Transistor computer
Further information: List of transistorized computers

The bipolar transistor was invented in 1947. From 1955 onwards transistors replaced vacuum tubes in computer designs,[99] giving rise to the "second generation" of computers. Initially the only devices available were germanium point-contact transistors.[100]



A bipolar junction transistor

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, indefinite, 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[101] 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.[102] Their first transistorised computer and the first in the world, was operational by 1953,[103] and a second version was completed there in April 1955.[104] 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,[105] 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 his 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.[106][107]

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.[108][109] 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.[110]

The Transistor Computer's design was adopted by the local engineering firm of Metropolitan-Vickers in their Metrovick 950, the first commercial transistor computer anywhere.[111] 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.[104]

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.

6.7.1 Transistorized peripherals

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.[112] 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.[113]

6.7.2 Supercomputers

The University of Manchester Atlas in January 1963

The early 1960s saw the advent of supercomputing. The Atlas Computer 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.[114] It was said that whenever Atlas went offline half of the United Kingdom's computer capacity was lost.[115] 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".[116]

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.[117] The CDC 6600, released in 1964, is generally considered the first supercomputer.[118][119] The CDC 6600 outperformed its predecessor, the IBM 7030 Stretch, by about a factor of three. With performance of about 1 megaFLOPS,[120] the CDC 6600 was the world's fastest computer from 1964 to 1969, when it relinquished that status to its successor, the CDC 7600.

6.8 The integrated circuit

The next great advance in computing power came with the advent of the integrated circuit. The idea of the integrated circuit was conceived by a radar scientist working for the Royal Radar Establishment of the Ministry of Defence, Geoffrey W.A. Dummer. Dummer presented the first public description of an integrated circuit at the Symposium on Progress in Quality Electronic Components in Washington, D.C. on 7 May 1952:[121]

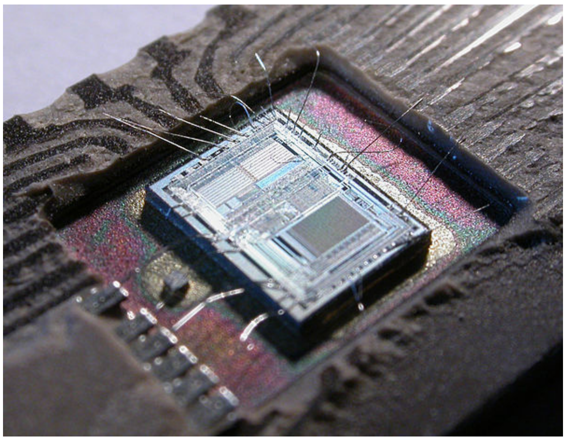
> With the advent of the transistor and the work on semi-conductors generally, it now seems possible to envisage electronic equipment in a solid block with no connecting wires.[122] The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electronic functions being connected directly by cutting out areas of the various layers".

The first practical ICs were invented by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor.[123] Kilby recorded his initial ideas concerning the integrated circuit in July 1958, successfully demonstrating the first working integrated example on 12 September 1958.[124] In his patent application of 6 February 1959, Kilby described his new device as "a body of semiconductor material ... wherein all the components of the electronic circuit are completely integrated."[125] The first customer for the invention was the US Air Force.[126]

Noyce also came up with his own idea of an integrated circuit half a year later than Kilby.[127] 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.

6.9 Post-1960 (integrated circuit based)

Main articles: History of computing hardware (1960s–present) and History of general purpose CPUs



Intel 8742 eight-bit microcontroller IC

The explosion in the use of computers began with "third-generation" computers, making use of Jack St. Clair Kilby's and Robert Noyce's independent invention of the integrated circuit (or microchip). This led to the invention of the microprocessor. While 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", it is largely undisputed that the first single-chip microprocessor was the Intel 4004,[128] designed and realized by Ted Hoff, Federico Faggin, and Stanley Mazor at Intel.[129]

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.[130] 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 automatons 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.[131] 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 the microcomputer, 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.

In April 1975 at the Hannover Fair, Olivetti presented the P6060, the world's first personal computer with built-in floppy disk: a central processing unit on two cards, code named PUCE1 and PUCE2, with TTL components. 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). It was in competition with a similar product by IBM that had an external floppy disk drive.

MOS Technology KIM-1 and Altair 8800, were sold as kits for do-it-yourselfers, as was the Apple I, soon afterward. The first Apple computer with graphic and sound capabilities came out well after the Commodore PET. Computing has evolved with microcomputer architectures, with features added from their larger brethren, now dominant in most market segments.

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.[132] 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.[133][134]

In the 21st century, multi-core CPUs became commercially available.[135] Content-addressable memory (CAM)[136] has become inexpensive enough to be used in networking, 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 during the 'transition' between logic states, except for leakage.

This has allowed computing to become a commodity 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 energy budget of the U.S.[137] 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.[138] Computing hardware and its software have even become a metaphor for the operation of the universe.[139]

6.10 Future

Although DNA-based computing and quantum computing are years or decades in the future, the infrastructure is being laid today, for example, with DNA origami on photolithography[140] and with quantum antennae for transferring information between ion traps.[141] By 2011, researchers had entangled 14 qubits.[142] Fast digital circuits (including those based on Josephson junctions and rapid single flux quantum technology) are becoming more nearly realizable with the discovery of nanoscale superconductors.[143]

Fiber-optic and photonic devices, which already have been used to transport data over long distances, are now entering the data center, side by side with CPU and semiconductor memory components. This allows the separation of RAM from CPU by optical interconnects.[144] IBM has created an integrated circuit with both electronic and optical (this is called *photonic*) information processing in one chip. This is denoted “CMOS-integrated nanophotonics” or (CINP).[145] One benefit of optical interconnects is that motherboards which formerly required a certain kind of system on a chip (SoC) can now move formerly dedicated memory and network controllers off the motherboards, spreading the controllers out onto the rack. This allows standardization of backplane interconnects and motherboards for multiple types of SoCs, which allows more timely upgrades of CPUs.[146]

An indication of the rapidity of development of this field can be inferred by the history of the seminal article.[147] 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 pace of development has continued, worldwide.[148][149][150]

6.11 See also

- Antikythera mechanism

- History of computing
- Information Age
- IT History Society
- Timeline of computing

6.12 Notes

[1] 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 4000 years) 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.

[2] Robson, Eleanor (2008), *Mathematics in Ancient Iraq*, ISBN 978-0-691-09182-2. p.5: calculi were in use in Iraq for primitive accounting systems as early as 3200–3000 BCE, with commodity-specific counting representation systems. Balanced accounting was in use by 3000–2350 BCE, and a sexagesimal number system was in use 2350–2000 BCE.

[3] Lazos 1994

[4] Noel Sharkey (July 4, 2007), *A programmable robot from 60 AD* **2611**, New Scientist

[5] A Spanish implementation of Napier's bones (1617), is documented in Montaner & Simon 1887, pp. 19–20.

[6] Kells, Kern & Bland 1943, p. 92

[7] Kells, Kern & Bland 1943, p. 82

[8] "...the single-tooth gear, like that used by Schickard, would not do for a general carry mechanism. The single-tooth gear works fine if the carry is only going to be propagated a few places but, if the carry has to be propagated several places along the accumulator, the force needed to operate the machine would be of such magnitude that it would do damage to the delicate gear works." Williams 1997, p. 128

[9] (fr) La Machine d'arithmétique, Blaise Pascal, Wikisource

[10] Marguin 1994, p. 48

[11] Maurice d'Ocagne (1893), p. 245 Copy of this book found on the CNAM site

[12] Mourlevat 1988, p. 12

[13] All nine machines are described in Vidal & Vogt 2011.

[14] See in particular, http://things-that-count.net

[15] As quoted in Smith 1929, pp. 180–181

[16] Leibniz 1703

[17] Binary-coded decimal (BCD) is a numeric representation, or character encoding, which is still widely used.

[18] Discovering the Arithmometer, Cornell University

[19] "Columbia University Computing History — Herman Hollerith". Columbia.edu. Retrieved 2010-01-30.

[20] U.S. Census Bureau: Tabulation and Processing

[21] http://www-03.ibm.com/ibm/history/history/year_1920.html

[22] http://www-03.ibm.com/ibm/history/history/decade_1930.html

[23] Eckert 1935

[24] Thomas J. Watson Astronomical Computing Bureau

[25] Eckert 1940, pp. 101=114. Chapter XII is "The Computation of Planetary Perturbations".

[26] Hunt 1998, pp. xiii–xxxvi

[27] Old Calculator Museum

[28] "Simple and Silent", *Office Magazine*, December 1961, p1244

[29] "'Anita' der erste tragbare elektonische Rechenautomat" [trans: "the first portable electronic computer"], *Buromaschinen Mechaniker*, November 1961, p207

[30] Halacy, Daniel Stephen (1970). *Charles Babbage, Father of the Computer*. Crowell-Collier Press. ISBN 0-02-741370-5.

[31] "Babbage". *Online stuff*. Science Museum. 2007-01-19. Retrieved 2012-08-01.

[32] "Let's build Babbage's ultimate mechanical computer". *opinion*. New Scientist. 23 December 2010. Retrieved 2012-08-01.

[33] http://cse.stanford.edu/classes/sophomore-college/projects-98/babbage/ana-mech.htm

[34] "The Babbage Pages: Calculating Engines". Projects.ex.ac.uk. 1997-01-08. Retrieved 2012-08-01.

[35] Tim Robinson (2007-05-28). "Difference Engines". Meccano.us. Retrieved 2012-08-01.

[36] Menabrea & Lovelace 1843

[37] Chua 1971, pp. 507–519

[38] "The Modern History of Computing". Stanford Encyclopedia of Philosophy.

[39] Ray Girvan, "The revealed grace of the mechanism: computing after Babbage", *Scientific Computing World*, May/June 2003

[40] Singer 1946

[41] Norden

[42] Coriolis 1836, pp. 5–9

[43] Turing 1937, pp. 230–265. Online versions: Proceedings of the London Mathematical Society Another version online.

[44] "von Neumann ... firmly emphasized to me, and to others I am sure, that the fundamental conception is owing to Turing—insofar as not anticipated by Babbage, Lovelace and others." Letter by Stanley Frankel to Brian Randell, 1972, quoted in Jack Copeland (2004) *The Essential Turing*, p22.

[45] Zuse, Horst. "Part 4: Konrad Zuse's Z1 and Z3 Computers". *The Life and Work of Konrad Zuse*. EPE Online. Archived from the original on 2008-06-01. Retrieved 2008-06-17.

[46] Smith 2007, p. 60

[47] Welchman 1984, p. 77

[48] Zuse

[49] "A Computer Pioneer Rediscovered, 50 Years On". *The New York Times*. April 20, 1994.

[50] Zuse, Konrad (1993). *Der Computer. Mein Lebenswerk.* (in German) (3rd ed.). Berlin: Springer-Verlag. p. 55. ISBN 978-3-540-56292-4.

[51] Crash! The Story of IT: Zuse at the Wayback Machine (archived March 18, 2008)

[52] "Electronic Digital Computers", *Nature* **162**, 25 September 1948: 487, Bibcode:1948Natur.162..487W, doi:10.1038/162487a0, retrieved 2009-04-10

[53] Da Cruz 2008

[54] J. Michael Dunn; Gary M. Hardegree (2001). *Algebraic methods in philosophical logic*. Oxford University Press US. p. 2. ISBN 978-0-19-853192-0.

[55] Shannon, Claude (1938). "A Symbolic Analysis of Relay and Switching Circuits". *Transactions of the American Institute of Electrical Engineers* **57**: 713–723. doi:10.1109/t-aiee.1938.5057767.

[56] Shannon 1940

[57] January 15, 1941 notice in the *Des Moines Register*

[58] Arthur W. Burks. *The First Electronic Computer*.

[59] Copeland, Jack (2006), *Colossus: The Secrets of Bletchley Park's Codebreaking Computers*, Oxford: Oxford University Press, pp. 101–115, ISBN 0-19-284055-X

[60] Welchman 1984, pp. 138–145, 295–309

[61] Copeland 2006

[62] Randell 1980, p. 9

[63] Budiansky 2000, p. 314

[64] "Bletchley's code-cracking Colossus", *BBC News*, 2 February 2010, retrieved 19 October 2012

[65] Fensom, Jim (8 November 2010), *Harry Fensom obituary*, retrieved 17 October 2012

[66] The Colossus Rebuild http://www.tnmoc.org/colossus-rebuild-story

[67] Randell, Brian; Fensom, Harry; Milne, Frank A. (15 March 1995), "Obituary: Allen Coombs", *The Independent*, retrieved 18 October 2012

[68] Brendan I. Loerner, "The World's First Computer Has Finally Been Resurrected" accessdate=2014-11-25

[69] The existence of Colossus was not known to American computer scientists, such as Gordon Bell and Allen Newell (1971) in their *Computing Structures*, a standard reference work in the 1970s

[70] Generations of Computers

[71] Copeland 2006, p. 104

[72] Enticknap, Nicholas (Summer 1998), "Computing's Golden Jubilee", *Resurrection* (The Computer Conservation Society) (20), ISSN 0958-7403, retrieved 19 April 2008

[73] "Early computers at Manchester University", *Resurrection* (The Computer Conservation Society) **1** (4), Summer 1992, ISSN 0958-7403, retrieved 7 July 2010

[74] http://www.computer50.org/mark1/notes.html#acousticdelay Why Williams-Kilburn Tube is a Better Name for the Williams Tube

[75] Kilburn, Tom (1990), "From Cathode Ray Tube to Ferranti Mark I", *Resurrection* (The Computer Conservation Society) **1** (2), ISSN 0958-7403, retrieved 15 March 2012

[76] *Early Electronic Computers (1946–51)*, University of Manchester, retrieved 16 November 2008

[77] Napper, R. B. E., *Introduction to the Mark 1*, The University of Manchester, retrieved 4 November 2008

[78] Lavington 1998, p. 20

[79] Pioneering Edsac computer to be built at Bletchley Park http://www.bbc.co.uk/news/technology-12181153

[80] Wilkes, W. V.; Renwick, W. (1950). "The EDSAC (Electronic delay storage automatic calculator)". *Math. Comp.* **4**: 61–65. doi:10.1090/s0025-5718-1950-0037589-7.

[81] The Manchester Small-Scale Experimental Machine, nicknamed "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. http://www.cl.cam.ac.uk/conference/EDSAC99/history.html. However, the Manchester Mark 1 of 1949 (not to be confused with the 1948 SSEM prototype) was available for university research in April 1949 http://www.computer50.org/mark1/MM1.html despite being still under development.

[82] "Pioneer computer to be rebuilt". *Cam* **62**: 5. Lent 2011. Check date values in: |date= (help) To be precise, EDSAC's first program printed a list of the squares of the integers from 0 to 99 inclusive.

[83] *EDSAC 99: 15-16 April 1999*, University of Cambridge Computer Laboratory, 1999-05-06, pp. 68, 69, retrieved 2013-06-29

[84] Wilkes, M. V. (1956). *Automatic Digital Computers*. New York: John Wiley & Sons. pp. 305 pages. QA76.W5 1956.

[85] Lavington 1998, p. 25

[86] Computer Conservation Society, *Our Computer Heritage Pilot Study: Deliveries of Ferranti Mark I and Mark I Star computers.*, retrieved 9 January 2010

[87] Lavington, Simon. "A brief history of British computers: the first 25 years (1948–1973).". British Computer Society. Retrieved 10 January 2010.

[88] Martin 2008, p. 24 notes that David Caminer (1915–2008) served as the first corporate electronic systems analyst, for this first business computer system, a Leo computer, part of J. Lyons & Company. LEO would calculate an employee's pay, handle billing, and other office automation tasks.

[89] Consumer Price Index (estimate) 1800–2014. Federal Reserve Bank of Minneapolis. Retrieved February 27, 2014.

[90] For example, Kara Platoni's article on Donald Knuth stated that "there was something special about the IBM 650", *Stanford Magazine*, May/June 2006

- Dr. V. M. Wolontis (August 18, 1955) "A Complete Floating-Decimal Interpretive System for the I.B.M. 650 Magnetic Drum Calculator — Case 20878" Bell Telephone Laboratories Technical Memorandum MM-114-37, Reported in IBM Technical Newsletter No. 11, March 1956, as referenced in IEEE *Annals of the History of Computing* (Volume:**8** , Issue: 1) January 1986

[91] Dudley, Leonard (2008), *Information Revolution in the History of the West*, Edward Elgar Publishing, p. 266, ISBN 978-1-84720-790-6

[92] IBM (1957), *SOAP II for the IBM 650* (PDF), C24-4000-0

[93] Horowitz & Hill 1989, p. 743

[94] Wilkes, M. V. (1992). "Edsac 2". *IEEE Annals of the History of Computing* **14** (4): 49–56. doi:10.1109/85.194055.

[95] The microcode was implemented as *extracode* on Atlas accessdate=20100209

[96] An Wang filed October 1949, US patent 2708722, "Pulse transfer controlling devices", issued 1955-05-17

[97] Magnetic tape will be the primary data storage mechanism when CERN's Large Hadron Collider comes online in 2008.

[98] IBM 1956

[99] Feynman, Leighton & Sands 1966, pp. 14-11 to 14–12

[100] Lavington 1998, pp. 34–35

[101] IBM_SMS 1960

[102] Lavington (1998), pp. 34–35

[103] Lavington 1998, p. 37

[104] Lavington (1998), p. 37

[105] Cooke-Yarborough, E. H. (June 1998), "Some early transistor applications in the UK", *Engineering and Science Education Journal* (IEE) **7** (3): 100–106, doi:10.1049/esej:19980301, ISSN 0963-7346, retrieved 7 June 2009 (subscription required)

[106] Cooke-Yarborough, E.H. (1957). *Introduction to Transistor Circuits*. Edinburgh: Oliver and Boyd. p. 139.

[107] Cooke-Yarborough, E.H. (June 1998). "Some early transistor applications in the UK". *Engineering and Science Education Journal* (London, UK: IEE) **7** (3): 100–106. doi:10.1049/esej:19980301. ISSN 0963-7346. Retrieved 2009-06-07.

[108] Lavington, Simon (1980). *Early British Computers*. Manchester University Press. p. 139. ISBN 0-7190-0803-4.

[109] Cooke-Yarborough, E. H. (1956). "transistor digital computer". *Proceedings of the IEE* (London, UK: IEE) **103B** (Supp 1–3): 364–70. ISSN 0956-3776.

[110] Lavington 1998, pp. 36–37

[111] "Metrovick".

[112] Allen Newell used remote terminals to communicate cross-country with the RAND computers, as noted in Simon 1991

[113] 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."—Mayo & Newcomb 2008

[114] Lavington 1998, p. 41

[115] Lavington 1998, pp. 44–45

[116] Lavington 1980, pp. 50–52

[117] *Hardware software co-design of a multimedia SOC platform* by Sao-Jie Chen, Guang-Huei Lin, Pao-Ann Hsiung, Yu-Hen Hu 2009 ISBN pages 70-72

[118] John Impagliazzo, John A. N. Lee (2004). *History of computing in education*. p. 172. ISBN 1-4020-8135-9.

[119] Richard Sisson, Christian K. Zacher (2006). *The American Midwest: an interpretive encyclopedia*. p. 1489. ISBN 0-253-34886-2.

[120]

[121] "The Hapless Tale of Geoffrey Dummer", (n.d.), (HTML), *Electronic Product News*, accessed 8 July 2008.

[122] Lott, Sara. "1958 – All semiconductor "Solid Circuit" is demonstrated". *A Timeline of Semiconductors in Computers*. Computer History Museum. Retrieved 4 September 2011.

[123] Kilby 2000

[124] *The Chip that Jack Built*, (c. 2008), (HTML), Texas Instruments, Retrieved 29 May 2008.

[125] Winston, Brian (1998). *Media Technology and Society: A History : From the Telegraph to the Internet*. Routledge. p. 221. ISBN 978-0-415-14230-4.

[126] "Texas Instruments – 1961 First IC-based computer". Ti.com. Retrieved 2012-08-13.

[127] Robert Noyce's Unitary circuit, US patent 2981877, "Semiconductor device-and-lead structure", issued 1961-04-25, assigned to Fairchild Semiconductor Corporation

[128] Intel_4004 1971

[129] The Intel 4004 (1971) die was 12 mm^2, composed of 2300 transistors; by comparison, the Pentium Pro was 306 mm^2, composed of 5.5 million transistors, according to Patterson & Hennessy 1998, pp. 27–39.

[130] In the defense field, considerable work was done in the computerized implementation of equations such as Kalman 1960, pp. 35–45

[131] Eckhouse & Morris 1979, pp. 1–2

[132] "Since 2005, its [Google's] data centers have been composed of standard shipping containers—each with 1,160 servers and a power consumption that can reach 250 kilowatts." — Ben Jai of Google, as quoted in Shankland 2009

[133] "If you're running 10,000 machines, something is going to die every day." —Jeff Dean of Google, as quoted in Shankland 2008.

[134] However, when an entire server farm fails today, the recovery procedures are currently still manual procedures, with the need for training the recovery team, even for the most advanced facilities. The initial failure was a power failure; the recovery procedure cited an inconsistent backup site, and the inconsistent backup site was outdated. Accessdate=2010-03-08

[135] Intel has unveiled a single-chip version of a 48-core CPU for software and circuit research in cloud computing: accessdate=2009-12-02. Intel has loaded Linux on each core; each core has an X86 architecture: accessdate=2009-12-3

[136] Kohonen 1980, pp. 1–368

[137] 2007 Energystar report, p. 4 accessdate=2013-08-18

[138] Walt Mossberg (9 July 2014) How the PC is merging with the smartphone accessdate=2014-07-09

[139] Smolin 2001, pp. 53–57.Pages 220–226 are annotated references and guide for further reading.

[140] Ryan J. Kershner, Luisa D. Bozano, Christine M. Micheel, Albert M. Hung, Ann R. Fornof, Jennifer N. Cha, Charles T. Rettner, Marco Bersani, Jane Frommer, Paul W. K. Rothemund & Gregory M. Wallraff (16 August 2009) "Placement and orientation of individual DNA shapes on lithographically patterned surfaces" *Nature Nanotechnology* publication information, supplementary information: DNA origami on photolithography doi:10.1038/nnano.2009.220

[141] M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel. Trapped-ion antennae for the transmission of quantum information. *Nature*, 2011; doi:10.1038/nature09800

[142] Thomas Monz, Philipp Schindler, Julio T. Barreiro, Michael Chwalla, Daniel Nigg, William A. Coish, Maximilian Harlander, Wolfgang Hänse, Markus Hennrich, and Rainer Blatt, (31 March 2011) "14-Qubit Entanglement: Creation and Coherence" *Phys. Rev. Lett.* **106** 13 http://link.aps.org/doi/10.1103/PhysRevLett.106.130506 doi:10.1103/PhysRevLett.106.130506

[143] Saw-Wai Hla et al., *Nature Nanotechnology* March 31, 2010 "World's smallest superconductor discovered". Four pairs of certain molecules have been shown to form a nanoscale superconductor, at a dimension of 0.87 nanometers. Access date 2010-03-31

[144] Tom Simonite, "Computing at the speed of light", *Technology Review* Wed., August 4, 2010 MIT

[145] Sebastian Anthony (Dec 10,2012), "IBM creates first commercially viable silicon nanophotonic chip", accessdate=2012-12-10

[146] Open Compute: Does the data center have an open future? accessdate=2013-08-11

[147] Burks, Goldstine & von Neumann 1947, pp. 1–464 reprinted in *Datamation*, September–October 1962. Note that *preliminary discussion/design* was the term later called *system analysis/design*, and even later, called *system architecture*.

[148] IEEE_Annals 1979 (*IEEE Annals of the History of Computing* online access)

[149] *DBLP* summarizes the *Annals of the History of Computing* year by year, back to 1995, so far.

[150] The fastest supercomputer of the top 500 was announced to be Tianhe-2 at the 2014 Supercomputing Conference, two years in a row, previously topping 2012's Titan, as of Monday, June 23, 2014.

6.13 References

- Backus, John (August 1978), "Can Programming be Liberated from the von Neumann Style?", *Communications of the ACM* **21** (8): 613, doi:10.1145/359576.359579, 1977 ACM Turing Award Lecture.

- Bell, Gordon; Newell, Allen (1971), *Computer Structures: Readings and Examples*, New York: McGraw-Hill, ISBN 0-07-004357-4.
- Bergin, Thomas J. (ed.) (November 13–14, 1996), *Fifty Years of Army Computing: from ENIAC to MSRC*, A record of a symposium and celebration, Aberdeen Proving Ground.: Army Research Laboratory and the U.S.Army Ordnance Center and School., retrieved 2008-05-17.
- Bowden, B. V. (1970), "The Language of Computers", *American Scientist* **58**: 43–53, Bibcode:1970AmSci..58...43B, retrieved 2008-05-17.
- Burks, Arthur W.; Goldstine, Herman; von Neumann, John (1947), *Preliminary discussion of the Logical Design of an Electronic Computing Instrument*, Princeton, NJ: Institute for Advanced Study, retrieved 2008-05-18.
- Chua, Leon O (September 1971), "Memristor—The Missing Circuit Element", *IEEE Transactions on Circuit Theory*, CT-18 (5): 507–519, doi:10.1109/TCT.1971.1083337.
- Cleary, J. F. (1964), *GE Transistor Manual* (7th ed.), General Electric, Semiconductor Products Department, Syracuse, NY, pp. 139–204, OCLC 223686427.
- Copeland, B. Jack (ed.) (2006), *Colossus: The Secrets of Bletchley Park's Codebreaking Computers*, Oxford, England: Oxford University Press, ISBN 0-19-284055-X.
- Coriolis, Gaspard-Gustave (1836), "Note sur un moyen de tracer des courbes données par des équations différentielles", *Journal de Mathématiques Pures et Appliquées*, series I (in French) **1**: 5–9, retrieved 2008-07-06.
- Cortada, James W. (2009), "Public Policies and the Development of National Computer Industries in Britain, France, and the Soviet Union, 1940–80", *Journal of Contemporary History* **44** (3): 493–512, doi:10.1177/0022009409104120, JSTOR 40543045.
- *CSIRAC: Australia's first computer* (– Scholar search), Commonwealth Scientific and Industrial Research Organisation (CSIRAC), June 3, 2005, retrieved 2007-12-21.
- Da Cruz, Frank (February 28, 2008), "The IBM Automatic Sequence Controlled Calculator (ASCC)", *Columbia University Computing History: A Chronology of Computing at Columbia University* (Columbia University ACIS), retrieved 2008-05-17.
- Davenport, Wilbur B., Jr; Root, William L. (1958), *An Introduction to the theory of Random Signals and Noise*, McGraw-Hill, pp. 112–364, OCLC 573270.
- Eckert, Wallace (1935), "The Computation of Special Perturbations by the Punched Card Method.", *Astronomical Journal* **44** (1034): 177, Bibcode:1935AJ.....44..177E, doi:10.1086/105298.
- Eckert, Wallace (1940), "XII: "The Computation of Planetary Perturbations"", *Punched Card Methods in Scientific Computation*, Thomas J. Watson Astronomical Computing Bureau, Columbia University, pp. 101–114, OCLC 2275308.
- Eckhouse, Richard H., Jr.; Morris, L. Robert (1979), *Minicomputer Systems: organization, programming, and applications (PDP-11)*, Prentice-Hall, pp. 1–2, ISBN 0-13-583914-9.
- Enticknap, Nicholas (Summer 1998), "Computing's Golden Jubilee", *Resurrection* (The Computer Conservation Society) (20), ISSN 0958-7403, retrieved 2008-04-19.
- Feynman, R. P.; Leighton, Robert; Sands, Matthew (1965), *Feynman Lectures on Physics: Mainly Mechanics, Radiation and Heat* **I**, Reading, Mass: Addison-Wesley, ISBN 0-201-02010-6, OCLC 531535.
- Feynman, R. P.; Leighton, Robert; Sands, Matthew (1966), *Feynman Lectures on Physics: Quantum Mechanics* **III**, Reading, Mass: Addison-Wesley, ASIN B007BNG4E0.
- Fisk, Dale (2005), *Punch cards*, Columbia University ACIS, retrieved 2008-05-19.
- Flamm, Kenneth (1987), *Targeting the Computer: Government Support and International Competition*, Washington, DC: Brookings Institution Press, ISBN 978-0-815-72852-8.
- Flamm, Kenneth (1988), *Creating the Computer: Government, Industry, and High Technology*, Washington, DC: Brookings Institution Press, ISBN 978-0-815-72850-4.
- Hollerith, Herman (1890), *In connection with the electric tabulation system which has been adopted by U.S. government for the work of the census bureau* (Ph.D. dissertation), Columbia University School of Mines.
- Horowitz, Paul; Hill, Winfield (1989), *The Art of Electronics* (2nd ed.), Cambridge University Press, ISBN 0-521-37095-7.
- Hunt, J. c. r. (1998), "Lewis Fry Richardson and his contributions to Mathematics, Meteorology and

Models of Conflict", *Ann. Rev. Fluid Mech.* **30** (1): XIII–XXXVI, Bibcode:1998AnRFM..30D..13H, doi:10.1146/annurev.fluid.30.1.0, retrieved 2008-06-15.

- IBM_SMS (1960), *IBM Standard Modular System SMS Cards*, IBM, retrieved 2008-03-06.
- IBM (September 1956), *IBM 350 disk storage unit*, IBM, retrieved 2008-07-01.
- IEEE_Annals (Series dates from 1979), *Annals of the History of Computing*, IEEE, retrieved 2008-05-19 Check date values in: |date= (help).
- Ifrah, Georges (2000), *The Universal History of Numbers: From prehistory to the invention of the computer.*, John Wiley and Sons, p. 48, ISBN 0-471-39340-1. Translated from the French by David Bellos, E.F. Harding, Sophie Wood and Ian Monk. Ifrah supports his thesis by quoting idiomatic phrases from languages across the entire world.
- Intel_4004 (November 1971), *Intel's First Microprocessor—the Intel 4004*, Intel Corp., retrieved 2008-05-17.
- Jones, Douglas W, *Punched Cards: A brief illustrated technical history*, The University of Iowa, retrieved 2008-05-15.
- Kalman, R.E. (1960), "A new approach to linear filtering and prediction problems", *Journal of Basic Engineering* **82** (1): 35–45, doi:10.1115/1.3662552, retrieved 2008-05-03.
- Kells; Kern; Bland (1943), *The Log-Log Duplex Decitrig Slide Rule No. 4081: A Manual*, Keuffel & Esser, p. 92.
- Kilby, Jack (2000), *Nobel lecture*, Stockholm: Nobel Foundation, retrieved 2008-05-15.
- Kohonen, Teuvo (1980), *Content-addressable memories*, Springer-Verlag, p. 368, ISBN 0-387-09823-2.
- Lavington, Simon (1998), *A History of Manchester Computers* (2 ed.), Swindon: The British Computer Society
- Lazos, Christos (1994), *Ο ΥΠΟΛΟΓΙΣΤΗΣ ΤΩΝ ΑΝΤΙΚΥΘΗΡΩΝ* [*The Antikythera Computer*], ΑΙΟΛΟΣ PUBLICATIONS GR.
- Leibniz, Gottfried (1703), *Explication de l'Arithmétique Binaire*.
- Lubar, Steven (May 1991), *"Do not fold, spindle or mutilate": A cultural history of the punched card*, archived from the original on 2006-10-25, retrieved 2006-10-31
- Manchester (1999), *Mark 1*, Computer History Museum, The University of Manchester, retrieved 2008-04-19
- Marguin, Jean (1994), *Histoire des instruments et machines à calculer, trois siècles de mécanique pensante 1642-1942* (in French), Hermann, ISBN 978-2-7056-6166-3
- Martin, Douglas (June 29, 2008), "David Caminer, 92 Dies; A Pioneer in Computers", *New York Times*: 24
- Mayo, Keenan; Newcomb, Peter (July 2008), "How the web was won: an oral history of the internet", *Vanity Fair* (Conde Nast): 96–117, retrieved 2012-05-05
- Mead, Carver; Conway, Lynn (1980), *Introduction to VLSI Systems*, Reading, Mass.: Addison-Wesley, ISBN 0-201-04358-0.
- Menabrea, Luigi Federico; Lovelace, Ada (1843), "Sketch of the Analytical Engine Invented by Charles Babbage", *Scientific Memoirs* **3**. With notes upon the Memoir by the Translator.
- Menninger, Karl (1992), *Number Words and Number Symbols: A Cultural History of Numbers*, Dover Publications. German to English translation, M.I.T., 1969.
- Montaner; Simon (1887), *Diccionario Enciclopédico Hispano-Americano (Hispano-American Encyclopedic Dictionary)*.
- Moye, William T. (January 1996), *ENIAC: The Army-Sponsored Revolution*, retrieved 2008-05-17.
- Norden, *M9 Bombsight*, National Museum of the USAF, retrieved 2008-05-17.
- Noyce, Robert US patent 2981877, Robert Noyce, "Semiconductor device-and-lead structure", issued 1961-04-25, assigned to Fairchild Semiconductor Corporation.
- Patterson, David; Hennessy, John (1998), *Computer Organization and Design*, San Francisco: Morgan Kaufmann, ISBN 1-55860-428-6.
- Mourlevat, Guy (1988), *Les machines arithmétiques de Blaise Pascal* (in French), Clermont-Ferrand: La Française d'Edition et d'Imprimerie
- Pellerin, David; Thibault, Scott (April 22, 2005), *Practical FPGA Programming in C*, Prentice Hall Modern Semiconductor Design Series Sub Series: PH Signal Integrity Library, pp. 1–464, ISBN 0-13-154318-0.
- Phillips, A.W.H., *The MONIAC*, Reserve Bank Museum, retrieved 2006-05-17.

- Reynolds, David (2010), "Science, technology, and the Cold War", in Leffler, Melvyn P.; Westad, Odd Arne, *The Cambridge History of the Cold War, Volume III: Endings*, Cambridge: Cambridge University Press, pp. 378–399, ISBN 978-0-521-83721-7.
- Rojas, Raul; Hashagen, Ulf (eds., 2000). *The First Computers: History and Architectures*. Cambridge: MIT Press. ISBN 0-262-68137-4.
- Schmandt-Besserat, Denise (1981), "Decipherment of the earliest tablets", *Science* **211** (4479): 283–285, Bibcode:1981Sci...211..283S, doi:10.1126/science.211.4479.283, PMID 17748027.
- Shankland, Stephen (May 30, 2008), *Google spotlights data center inner workings*, Cnet, retrieved 2008-05-31.
- Shankland, Stephen (April 1, 2009), *Google uncloaks once-secret server*, Cnet, retrieved 2009-04-01.
- Shannon, Claude E. (1940), *A symbolic analysis of relay and switching circuits*, Massachusetts Institute of Technology, Dept. of Electrical Engineering.
- Simon, Herbert A. (1991), *Models of My Life*, Basic Books, Sloan Foundation Series.
- Singer (1946), *Singer in World War II, 1939–1945 — the M5 Director*, Singer Manufacturing Co., retrieved 2008-05-17.
- Smith, David Eugene (1929), *A Source Book in Mathematics*, New York: McGraw-Hill, pp. 180–181.
- Smolin, Lee (2001), *Three roads to quantum gravity*, Basic Books, pp. 53–57, ISBN 0-465-07835-4. Pages 220–226 are annotated references and guide for further reading.
- Steinhaus, H. (1999), *Mathematical Snapshots* (3rd ed.), New York: Dover, pp. 92–95, p. 301.
- Stern, Nancy (1981), *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers*, Digital Press, ISBN 0-932376-14-2.
- Stibitz, George US patent 2668661, George Stibitz, "Complex Computer", issued 1954-02-09, assigned to American Telephone & Telegraph Company.
- Taton, René (1969), *Histoire du calcul. Que sais-je ? n° 198* (in French), Presses universitaires de France
- Turing, A.M. (1936), "On Computable Numbers, with an Application to the Entscheidungsproblem", *Proceedings of the London Mathematical Society*, 2 (1937) **42** (1): 230–65, doi:10.1112/plms/s2-42.1.230 (and Turing, A.M. (1938), "On Computable Numbers, with an Application to the Entscheidungsproblem: A correction", *Proceedings of the London Mathematical Society*, 2 (1937) **43** (6): 544–6, doi:10.1112/plms/s2-43.6.544)Other online versions: Proceedings of the London Mathematical Society Another link online.
- Ulam, Stanislaw (1976), *Adventures of a Mathematician*, New York: Charles Scribner's Sons, (autobiography).
- Vidal, Nathalie; Vogt, Dominique (2011), *Les Machines Arithmétiques de Blaise Pascal* (in French), Clermont-Ferrand: Muséum Henri-Lecoq, ISBN 978-2-9528068-4-8
- von Neumann, John (June 30, 1945), *First Draft of a Report on the EDVAC*, Moore School of Electrical Engineering: University of Pennsylvania.
- Wang, An US patent 2708722, An Wang, "Pulse transfer controlling devices", issued 1955-05-17.
- Welchman, Gordon (1984), *The Hut Six Story: Breaking the Enigma Codes*, Harmondsworth, England: Penguin Books, pp. 138–145, 295–309.
- Wilkes, Maurice (1986), "The Genesis of Microprogramming", *Ann. Hist. Comp.* **8** (2): 115–126.
- Williams, Michael R. (1997), *History of Computing Technology*, Los Alamitos, California: IEEE Computer Society, ISBN 0-8186-7739-2
- Ziemer, Roger E.; Tranter, William H.; Fannin, D. Ronald (1993), *Signals and Systems: Continuous and Discrete*, Macmillan, p. 370, ISBN 0-02-431641-5.
- Zuse, *Z3 Computer (1938–1941)*, retrieved 2008-06-01.
- Zuse, Konrad (2010) [1984], *The Computer – My Life* Translated by McKenna, Patricia and Ross, J. Andrew from: *Der Computer, mein Lebenswerk (1984)* (in English translated from German), Berlin/Heidelberg: Springer-Verlag, ISBN 978-3-642-08151-4

6.14 Further reading

- Ceruzzi, Paul E., A History of Modern Computing, MIT Press, 1998

6.15 External links

- Obsolete Technology — Old Computers
- History of calculating technology
- Historic Computers in Japan

- The History of Japanese Mechanical Calculating Machines
- Computer History — a collection of articles by Bob Bemer
- 25 Microchips that shook the world — a collection of articles by the Institute of Electrical and Electronics Engineers

Chapter 7

Instructions per second

Instructions per second (**IPS**) is a measure of a computer's processor speed. Many reported IPS values have represented "peak" execution rates on artificial instruction sequences with few branches, whereas realistic workloads typically lead to significantly lower IPS values. The performance of the memory hierarchy also greatly affects processor performance, an issue barely considered in MIPS calculations. Because of these problems, synthetic benchmarks such as SPECint are now generally used to estimate computer performance in commonly used applications, and raw IPS has fallen into disuse.

The term is commonly used in association with a numeric value such as **thousand instructions per second** (**kIPS**), **million instructions per second** (**MIPS**), **Giga instructions per second** (**GIPS**), or **million operations per second** (**MOPS**).

7.1 Thousand instructions per second

Before standard benchmarks were available, average speed rating of computers was based on calculations for a mix of instructions with the results given in kilo Instructions Per Second (kIPS). The most famous was the **Gibson Mix**, produced by Jack Clark Gibson of IBM for scientific applications. Other ratings, such as the ADP mix which does not include floating point operations, were produced for commercial applications. Computer Speeds From Instruction Mixes pre-1960 to 1971 has results for around 175 computers, providing scientific (Gibson) and commercial (ADP) ratings. For IBM, the earliest Gibson Mix calculations shown are the 1954 IBM 650 at 0.06 kIPS and 1956 IBM 705 at 0.5 kIPS. The results are mainly for IBM and others known as the BUNCH — Burroughs, UNIVAC, NCR, CDC, and Honeywell.

The thousand instructions per second (kIPS) unit is rarely used today, as most current microprocessors can execute at least a million instructions per second.

7.2 Millions of instructions per second

The speed of a given CPU depends on many factors, such as the type of instructions being executed, the execution order and the presence of branch instructions (problematic in CPU pipelines). CPU instruction rates are different from clock frequencies, usually reported in Hz, as each instruction may require several clock cycles to complete or the processor may be capable of executing multiple independent instructions at once. MIPS can be useful when comparing performance between processors made from a similar architecture (e.g. Microchip branded microcontrollers). However, MIPS are difficult to compare between CPU architectures.[1]

For this reason, MIPS has become not a measure of instruction execution speed, but task performance speed compared to a reference. In the late 1970s, minicomputer performance was compared using *VAX MIPS*, where computers were measured on a task and their performance rated against the VAX 11/780 that was marketed as a *1 MIPS* machine. (The measure was also known as the *VAX Unit of Performance* or **VUP**.) This was chosen because the 11/780 was roughly equivalent in performance to an IBM System/370 model 158-3, which was commonly accepted in the computing industry as running at 1 MIPS.

Many minicomputer performance claims were based on the Fortran version of the Whetstone benchmark, giving Millions of Whetstone Instructions Per Second (MWIPS). The VAX 11/780 with FPA (1977) runs at 1.02 MWIPS.

Effective MIPS speeds are highly dependent on the programming language used. The Whetstone Report has a table showing MWIPS speeds of PCs via early interpreters and compilers up to modern languages. The first PC compiler was for BASIC (1982) when a 4.8 MHz 8088/87 CPU obtained 0.01 MWIPS. Results on a 2.4 GHz Intel Core 2 Duo (1 CPU 2007) vary from 9.7 MWIPS using BASIC Interpreter, 59 MWIPS via BASIC Compiler, 347 MWIPS using 1987 Fortran, 1,534 MWIPS through HTML/Java to 2,403 MWIPS using a modern C/C++ compiler.

For the most early 8-bit and 16-bit microprocessors, performance was measured in thousand instructions per second (1 kIPS = 0.001 MIPS).

zMIPS refers to the MIPS measure used internally by IBM to rate its mainframe servers (zSeries, IBM System z9, and IBM System z10).

Weighted million operations per second (WMOPS) is a similar measurement, used for audio codecs.

7.3 Timeline of instructions per second

Note: **Bold** highlight indicates the next step-up in terms of the highest known MIPS figures of their time.

7.4 Historic data

- Computer Speeds From Instruction Mixes pre-1960 to 1971 (kIPS 175 systems)
- Computer Speed Claims 1980 to 1996 (MIPS >2000 systems)
- PC CPU Performance Comparisons %MIPS/MHz

7.5 See also

- Benchmark (computing)
- BogoMips (measurement of CPU speed made by the Linux kernel)
- Cycles per instruction
- Dhrystone MIPS (DMIPS)
- FLOPS (floating-point operations per second)
- Instructions per cycle
- Million service units (MSU)
- Orders of magnitude (computing)
- Performance per watt

7.6 References

[1] Ted MacNeil. "Don't be Misled by MIPS". IBM magazine.

[2] *US Steel News*. 15-20. Industrial Relations Department of The United States Steel Corporation of Delaware. 1950–1955. p. 29.

[3] MCS4 > IntelP4004

[4] http://www.jcmit.com/cpu-performance.htm

[5] http://web.archive.org/web/20120424231244/http://www.depi.itch.edu.mx/apacheco/asm/Intel_cpus.htm

[6] http://www.drolez.com/retro/

[7] 2 cycles per instruction

[8] http://museum.ipsj.or.jp/en/computer/super/0003.html

[9] http://homepage1.nifty.com/KSudou-NET/ks0D0D03.htm

[10] 1 instruction per cycle

[11] 4 cycles per instruction = 0.25 instructions per cycle

[12] http://archive.org/stream/bitsavers_inteldataSngleComponent8BitMicrocomputerDataSheet1_846962/8048_8035_HMOS_Single_Component_8-Bit_Microcomputer_DataSheet_1980

[13] http://web.archive.org/web/20120219195401/http://www.cityofberwyn.com/simulation/gameHardware/G80ref1.20.txt

[14] http://www.system16.com/hardware.php?id=735

[15] Sega G80: Zilog Z80 @ 8 MHz (1.16 MIPS), 2× Intel 8035/8039 @ 3.12 MHz (6.24 MIPS)

[16] 10% faster than 68000 (0.175 MIPS per MHz)

[17] NEC V20/V30: 250 nanoseconds per instruction @ 8 MHz

[18] Namco Pole Position: Zilog Z80 @ 3.072 (0.445 MIPS), 2× Zilog Z8002 @ 3.072 MHz (1.536 MIPS), 4× Fujitsu MB8843/MB8844 @ 1.54 MHz (6.16 MIPS)

[19] LINKS-1 Computer Graphics System: 257× Zilog Z8001 at 10 MHz (2.5 MIPS) each

[20] http://www.ti.com/lit/ds/symlink/tms320ss16.pdf

[21] MC68020 Product Summary Page

[22] http://digital.hitachihyoron.com/pdf/1985/08/1985_08_05.pdf

[23] http://www.datasheetarchive.com/dlmain/Datasheets-13/DSA-246134.pdf

[24] 1 instruction per cycle

[25] Sega System 16: Hitachi-Motorola 68000 @ 10 MHz (1.75 MIPS), NEC-Zilog Z80 @ 4 MHz (0.58 MIPS) , Intel 8751 @ 8 Mhz (8 MIPS), Intel 8048 @ 6 MHz (6 MIPS)

[26] http://books.google.co.uk/books?id=KzoEAAAAMBAJ&pg=PT22

[27] http://ipsj.ixsq.nii.ac.jp/ej/?action=pages_view_main&active_action=repository_view_main_item_detail&item_id=59745&item_no=1&page_id=13&block_id=8

[28] http://books.google.co.uk/books?id=KU7dCBpP7fsC&pg=PA130

[29] MC68030 Product Summary Page

[30] http://tronweb.super-nova.co.jp/tronvlsicpu.html

[31] http://historyofracinggames.files.wordpress.com/2007/06/060-1987-drivers-eyes-1989-winning-run.pdf

[32] http://pdf.datasheetcatalog.com/datasheet/analogdevices/ADSP-2100KG.pdf

[33] Namco System 21 hardware: 5× Texas Instruments TMS320C20 @ 25 MHz (62.5 MIPS), 2× Motorola 68000 @ 12.288 MHz (4.301 MIPS), Motorola 68020 @ 12.5 MHz (3.788 MIPS), Hitachi HD63705 @ 2.048 MHz (2.048 MIPS), Motorola 6809 @ 3.072 MHz (1.29 MIPS)

[34] http://alacron.com/index.php?src=gendocs&ref=Inteli860_basedBusBoardsFT_200_VME&category=news

[35] Atari Hard Drivin' hardware: Motorola 68000 @ 7 MHz (1.225 MIPS), Motorola 68010 @ 7 MHz (1.348 MIPS), 3× Texas Instruments TMS34010 @ 50 MHz (18 MIPS), Analog Devices ADSP-2100 @ 8 MHz (8 MIPS), Texas Instruments TMS32010 @ 20 MHz (5 MIPS)

[36] http://www.degruyter.com/dg/viewarticle/j\protect\char"0024\relax002fpiko.1990.13.issue-4\protect\char"0024\relax002fpiko.1990.13.4.205\protect\char"0024\relax002fpiko.1990.13.4.205.xml;jsessionid=2928071D864D5E4F9045C8A209E7AA94

[37] http://www.top500.org/system/170813

[38] MC68040 Product Summary Page

[39] Namco System 21 (Galaxian[3]) hardware: 80× Texas Instruments TMS320C25 @ 40 MHz (1600 MIPS), 5× Motorola 68020 @ 24.576 MHz (37.236 MIPS) Motorola 68000 @ 12.288 MHz (2.15 MIPS), 10× Motorola 68000 @ 12 MHz (21 MIPS)

[40] http://books.google.co.uk/books?id=sc0wyeolS8cC&pg=PA97

[41] Digital's 21064 Microprocessor, Digital Equipment Corporation (c1992) accessdate=2009-08-29

[42] http://www.system16.com/hardware.php?id=832

[43] http://dl.acm.org/citation.cfm?id=623816

[44] http://www.netlib.org/performance/html/dhrystone.data.col0.html

[45] 24× MIPS R4400 (2040 MIPS), 12× Intel i860 (600 MIPS)

[46] http://museum.ipsj.or.jp/en/computer/super/0020.html

[47] http://www.fujitsu.com/global/Images/fujitsu-contribution-to-hpc.pdf

[48] http://www.segatech.com/technical/saturnspecs/

[49] Tomshardware Cpu chart 2004

[50] PIC16F84A

[51] http://www.fermimn.gov.it/inform/materiali/evarchi/motorola/603e_fs.pdf

[52] Atmel Corporation - Atmel AVR 8- and 32-bit - megaAVR

[53] SiSoftware Zone

[54] http://www.segatech.com/technical/cpu/

[55] http://www.segatech.com/archives/january1998.html

[56] "Zilog Sees New Lease of Life for Z80 in Internet Appliances". *Computergram International*. 1999.

[57] Sega Naomi Multiboard hardware: 16× Hitachi SH-4 at 200 MHz (5760 MIPS), 16× ARM7 at 45 MHz (640 MIPS)

[58] Freescale Semiconductor - MPC8272 PowerQUICC II Processor Family

[59] http://www.frc.ri.cmu.edu/~{}hpm/book97/ch3/processor.list.txt

[60] http://www.datasheetarchive.com/ZISC78-datasheet.html

[61] Anandtech ARM Cortex A7 architecture comparison

[62] NEC Earth Simulator: 5,120× NEC SX-6 at 500 MHz (28,293,540 MIPS)

[63] PIC10F200

[64] Microchip Technology Debuts Industry's First 6-Pin Microcontrollers: The World's Smallest Microcontroller

[65] ARM Cortex-M3

[66] Nios II Performance Benchmarks

[67]

[68] mini-itx.com - epia px 10000 review

[69] ARM Cortex-A Series Comparison

[70] CPU Charts 2007 - Tom's Hardware

[71] Cortex-R4 Processor

[72] [http://www.mips.com/products/cores/32-64-bit-cores/mips32-24k/ MIPS32 24K]

[73] Synthetics, Continued - Tom's Hardware : Intel's Core 2 Quadro Kentsfield: Four Cores on a Rampage

[74] Design Reuse - needs free registration

[75] Merritt, Rick (5 February 2007). "Startup takes PowerPC to 25 W". *EE Times*. UBM Tech. Retrieved 20 November 2012.

[76] OC Workbench

[77] Synthetic - Sandra CPU - Tom's Hardware : Intel Core 2 Extreme QX9770: Paper Tiger?

[78] Tom's Hardware Cpu Charts 2010

[79] Cortex-M0 Processor

[80] EEE Journal

[81] XtremeSystems Member Synthetic - Sandra CPU

[82] K computer: 88,128× Fujitsu SPARC64 VIIIfx @ 2 GHz each

[83] Overclock3D - Sandra CPU

[84] http://www.top500.org/system/176929

[85] Tom's Hardware

[86] Samsung Exynos 5250 Announcement

[87] http://www.guru3d.com/articles-pages/core-i5-2500k-and-core-i7-2600k-review,13.html

[88] Tom's Hardware - Desktop CPU Charts 2011: Sandra 2010 Pro ALU

[89] HardOCP Bulldozer Desktop Performance - Synthetic Benchmarks

[90] http://www.cpu-world.com/benchmarks/browse/910_80,965_61,993_80,1035_96/?c_test=6&PROCESS=Show+Selected

[91] Tom's Hardware - Benchmark Results: Synthetics

[92] HardOCP - Synthetic Benchmarks

[93] http://versus.com/en/amd-fx-8350-black-edition-vs-intel-core-i7-4770k

[94] - Notebookcheck

[95] http://www.notebookcheck.net/Intel-Core-i7-Desktop-4770K-Notebook-Processor.93553.0.html

[96] http://techgage.com/print/core-i7-5960x-extreme-edition-review-intels-overdue-desktop-8-core-is-here/

7.7 Text and image sources, contributors, and licenses

7.7.1 Text

- **Classes of computers** *Source:* http://en.wikipedia.org/wiki/Classes%20of%20computers?oldid=648979183 *Contributors:* William Avery, Pnm, Tobias Bergemann, Giftlite, Ketil, Discospinster, Rich Farmbrough, Orbst, Diego Moya, RJFJR, Amorymeltzer, RainbowOfLight, Mandarax, Rjwilmsi, Bruce1ee, Teddyb, DeadEyeArrow, Saric, Ybbor, Rwwww, Eenu, FrozenPurpleCube, SmackBot, KnowledgeOfSelf, Henriok, Bigbluefish, C.Fred, Gilliam, Chris the speller, J. Spencer, Salmar, Can't sleep, clown will eat me, OrphanBot, JzG, Cbrown1023, Ostrolphant, Doyley, Jephir, R'n'B, Eliz81, NewEnglandYankee, KylieTastic, S, Signalhead, Philip Trueman, Softtest123, Dirkbb, Gangstammar, Keilana, Flyer22, Anim8er, JohnnyMrNinja, RobinHood70, Rilak, Excirial, Eeekster, Cenarium, Ankaraj.marri04, InfinityMinusOneMRV, 2, Roxy the dog, Mitch Ames, Zodon, Thebestofall007, Addbot, Jncraton, Peter Flass, AnomieBOT, Materialscientist, Anna Frodesiak, NobelBot, Shadowjams, Prari, Inc ru, DivineAlpha, Pinethicket, Ryoohkies, JamesGrimshaw, Jeffrd10, Stroppolo, EmausBot, RA0808, Solarra, K6ka, Christina Silverman, Makecat, Bromador, Donner60, Bulwersator, Gaurav7373, ClueBot NG, Rigorimpossible, O.Koslowski, S 90164, Wbm1058, Hr.hanafi, Vogone, Saed11072, Lugia2453, Frosty, Graphium, Johny.JAson, Tentinator, Thatjewishguy829, THATONEGUY698, Troybenavidez, Ginsuloft, Quenhitran, Trycytutu, Haroldok, Filedelinkerbot, Pinki kumari11, QwertyUsereditor, Kartik K07, GeorginaMat and Anonymous: 165
- **List of computer size categories** *Source:* http://en.wikipedia.org/wiki/List%20of%20computer%20size%20categories?oldid=646772545 *Contributors:* Pascal666, Alvestrand, Discospinster, Alinor, RHaworth, TomTheHand, Toussaint, Mandarax, Bgwhite, Gardar Rurak, Welsh, Rwwww, Palapa, Gilliam, Gold heart, McNeight, Darkildor, Cydebot, Kozuch, Marokwitz, Gwern, Conquerist, The Anonymous One, GL1zdA, SieBot, Ainlina, Martarius, Rilak, Canis Lupus, Kleeklee, Galzigler, Zodon, Addbot, Ramu50, Tascsoftwareirl, KitchM, Kookyunii, Materialscientist, In2thats12, Callanecc, DARTH SIDIOUS 2, Angrytoast, Bromador, ClueBot NG, Snotbot, Wbm1058, Riley Huntley, Karverstudio, Rotlink, GeorginaMat and Anonymous: 36
- **Torpedo Data Computer** *Source:* http://en.wikipedia.org/wiki/Torpedo%20Data%20Computer?oldid=631697871 *Contributors:* SimonP, RTC, Michael Hardy, Ineuw, Vroman, Wik, Riddley, Paul Klenk, Jooler, Kudz75, Sam, Rich Farmbrough, SlaveToTheWage, Rjwilmsi, Gaius Cornelius, Open2universe, Alureiter, Hmains, Chris the speller, Bluebot, Trekphiler, Ziggle, SmilingFace, Pinecone, Ergative rlt, Tawkerbot2, CMG, Aldis90, DulcetTone, Rees11, BilCat, Sagabot, Glrx, Robert1947, Lightmouse, Loren.wilton, Binksternet, Pekelney, Mikaey, Carriearchdale, Thewellman, Auragoneboy, Addbot, Magus732, Lightbot, Yobot, AnomieBOT, Ph4g3, Theoprakt, Citation bot, FrescoBot, LucienBOT, Trappist the monk, DexDor, GoingBatty, ClueBot NG, Sca1ey, BG19bot, MangoWong, BattyBot and Anonymous: 16
- **Analog computer** *Source:* http://en.wikipedia.org/wiki/Analog%20computer?oldid=644949856 *Contributors:* The Anome, Malcolm Farmer, Andre Engels, LA2, Waveguy, Topory, Nealmcb, AdSR, Michael Hardy, Liftarn, Ixfd64, Egil, Ellywa, ThirdParty, William M. Connolley, Angela, Kevin Baas, BenKovitz, Tim Retout, Smack, Vroman, Charles Matthews, Timwi, Dysprosia, Greenrd, Maximus Rex, Owen, Lumos3, Twang, Robbot, AlainV, Rursus, Blainster, Wikibot, Wile E. Heresiarch, Carnildo, Ancheta Wis, Giftlite, Wizzy, Levin, Duncharris, Gracefool, Foobar, Isidore, Gadfium, Physicist, Sonjaaa, Bumm13, Halo, Icairns, Discospinster, Rich Farmbrough, ArnoldReinhold, Ben Standeven, Daemondust, Coolcaesar, Nigelj, Viriditas, La goutte de pluie, Mdd, Arthena, CyberSkull, Diego Moya, RoySmith, Wtshymanski, Rick Sidwell, Cburnett, Sleigh, DV8 2XL, Gene Nygaard, Bookandcoffee, Dennis Bratland, Georgia guy, Ataru, Asav, Robert K S, Tabletop, Wikiklrsc, Waldir, Graham87, Margosbot, SuperDude115, TheDJ, Swtpc6800, Chobot, Frappyjohn, Subtractive, YurikBot, Wavelength, RussBot, Dbulwink, Gaius Cornelius, Sanguinity, R Pollack, Dialectric, Welsh, Johantheghost, Rhynchosaur, Claygate, Rwwww, SmackBot, JohnPomeranz, Jagged 85, Ssbohio, Mdd4696, Man with two legs, Powo, Xaosflux, Drttm, Buck Mulligan, Hmains, ERcheck, Snori, Hibernian, Dual Freq, Antonrojo, Sholto Maud, Furby100, JonHarder, Pooresd, Kcordina, Tlusťa, Normxxx, Digresser, Dannywein, Ziggle, Ohconfucius, Attys, Vgy7ujm, Codepro, IronGargoyle, Nagle, Wmattis, Dicklyon, Mets501, Dr.K., Peyre, Phuzion, Twas Now, Blehfu, Pjbflynn, Tawkerbot2, CRGreathouse, CmdrObot, Nczempin, Davnor, Chrislk02, Gimmetrow, Malleus Fatuorum, Thijs!bot, Epbr123, Headbomb, Gerry Ashton, Nezzadar, Dawnseeker2000, Escarbot, AntiVandalBot, Viscosipede, Acarballeira, Shirt58, Doktor Who, JAnDbot, Dereckson, Bongwarrior, Yakushima, Swpb, Nikevich, WhatamIdoing, LorenzoB, Lenticel, Swordsman04, MartinBot, GoldenMeadows, Sm8900, Keith D, Yonaa, R'n'B, Tgeairn, Ceros, J.delanoy, Herbythyme, KILNA, SharkD, LordAnubisBOT, AntiSpamBot, Belovedfreak, DorganBot, Mlewis000, VolkovBot, TXiKiBoT, Java7837, Rei-bot, Rick Jelliffe, Madhero88, MCTales, Oscillon, Dmcq, Donped, Missy Prissy, Soler97, مترجم05, Lightmouse, OKBot, Fakhredinblog, Canglesea, ClueBot, Binksternet, Niceguyedc, Pekelney, Eeekster, John Nevard, Posix memalign, Esbboston, Cexycy, Dekisugi, Ankaraj.marri04, Egmontaz, InternetMeme, Terry0051, Danny galaga, BodhisattvaBot, Dthomsen8, Libcub, Alexius08, MystBot, P.r.newman, Coffee joe, Cantaloupe2, Mathew Rammer, ProperFraction, Habanero-tan, Herr Gruber, RW Dutton, Lightbot, Softy, Legobot, Luckas-bot, Yobot, OrgasGirl, Bunnyhop11, Brian in denver, AnomieBOT, 1exec1, Jim1138, Materialscientist, Xqbot, Transity, Gfreemanphd, Asijut, Gumok, GrouchoBot, RibotBOT, Pent112, FrescoBot, Tobby72, Jc3s5h, Alarics, JMS Old Al, Whtowl2001, HamburgerRadio, Citation bot 1, Beao, TobeBot, Ripchip Bot, Balph Eubank, DASHBot, EmausBot, WikitanvirBot, Tommy2010, Serketan, Bethnim, Knight1993, East of Borschov, Gz33, EdoBot, Uziel302, ClueBot NG, Jostikas, Widr, Helpful Pixie Bot, Wbm1058, DBigXray, JokerWild11, BG19bot, Northamerica1000, MusikAnimal, GMRE, Francoisguay, Jonastyleranderson, Mariam Asatryan, Autodidaktos, ChrisGualtieri, Mbit, Bjfwiki, Kupraios, Johny.JAson, LiveRail, Bleahy48, Fitzcarmalan, Lucasdealmeidasm, SIHAEN, GeorginaMat, Byro Chimel and Anonymous: 200
- **Deltar** *Source:* http://en.wikipedia.org/wiki/Deltar?oldid=583660684 *Contributors:* Pnm, TheDJ, Nikevich, The Thing That Should Not Be, Addbot, Io Herodotus and Anonymous: 1
- **History of computing hardware** *Source:* http://en.wikipedia.org/wiki/History%20of%20computing%20hardware?oldid=649064108 *Contributors:* AxelBoldt, The Epopt, 0, Mav, Robert Merkel, Khendon, Arvindn, Aldie, Matusz, PierreAbbat, SimonP, Ellmist, Mintguy, Arno, Lisiate, Frecklefoot, Edward, RTC, Michael Hardy, Lexor, Dante Alighieri, Dominus, Nixdorf, Liftarn, Drjan, Chinju, Karada, Arpingstone, Iluvcapra, 7265, Stw, Ahoerstemeier, William M. Connolley, Notheruser, Angela, Darkwind, Glenn, Cyan, LouI, Susurrus, Cimon Avaro, EdH, Rob Hooft, Dwo, Vroman, Timwi, Harris7, Dmsar, Ww, Denni, Sbwoodside, Birkett, Tpbradbury, Timothy Muggli, David Shay, Jnc, Tempshill, Wellington, Omegatron, Wernher, Samsara, Thue, Bevo, Topbanana, Mackensen, Raul654, Chrisjj, Secretlondon, David.Monniaux, Josephbui, Ke4roh, PBS, Jmabel, Verbose, Lowellian, Gandalf61, Sverdrup, Blainster, Diderot, Halibutt, ElBenevolente, Superm401, SpellBott, Mfc, Lysy, David Gerard, Snobot, Ancheta Wis, Giftlite, DocWatson42, Haeleth, Laurens, Geeoharee, Tom harrison, Lupin, Everyking, Dune, Markus Kuhn, Fanf, Matt Crypto, Jackol, Bobblewik, Z3, Chowbok, Utcursch, Gdr, Quadell, Beland, WhiteDragon, Gene s, Michael Rowe, Thincat, GeoGreg, Marc Mongenet, Neutrality, Krp, Ukexpat, Coffeehood, Discospinster, Rich Farmbrough, Leibniz, Vsmith, Pixel8, ArnoldReinhold, Topynate, MeltBanana, Michael Zimmermann, Paul August, Sergei Frolov, Bender235, Alancookie, Pmcm, CanisRufus, Zscout370, Joanjoc, Bobo192, Denorris, Irrbloss, Smalljim, Colin Douglas Howell,

TheProject, Zygmunt lozinski, Notafish, Officiallyover, Mdd, Alansohn, Enirac Sum, Guy Harris, Andrewpmk, Riana, Goldom, Lightdarkness, Mailer diablo, Polyphilo, Velella, Saga City, Wtshymanski, Suruena, TenOfAllTrades, Gunter, Redvers, TheCoffee, Vmlinuz, Marcelo1229, Angr, Camw, Asav, Wackyvorlon, Brunnock, Jacobolus, Davidkazuhiro, Robert K S, ^demon, CaptainTickles, Ruud Koot, Pixeltoo, Cbdorsett, Wikiklrsc, Jacj, Driftwoodzebulin, Marudubshinki, Que, Rnt20, Graham87, Don Braffitt, BD2412, Dweinberger, Josh Parris, Ketiltrout, Rjwilmsi, Commander, JoshuacUK, Bhaak, Oblivious, EvilMoFo, Bubba73, Boccobrock, Brighterorange, Ian Dunster, DemonStar55, Josephs1, Yamamoto Ichiro, Lonestarnot, David jones, RobertG, Greg321, Who, Gurch, TheDJ, Ballas, Alphachimp, Vossman, SteveBaker, Chobot, Bgwhite, Wavelength, Borgx, Crotalus horridus, Hairy Dude, RussBot, Me and, Splash, Balancer, Groogle, Rada, Lucinos, Stephenb, Manop, Gaius Cornelius, Ksyrie, Wgungfu, Eddie.willers, NawlinWiki, The Merciful, Rieger, Grafen, Trovatore, Seeaxid, Davechatting, Jpbowen, Raven4x4x, Tony1, Adicarlo, Daniel C, Emijrp, Zzuuzz, Raistolo, Spondoolicks, Th1rt3en, Livitup, Petri Krohn, Loginer, Nzeemin, ArielGold, Curpsbot-unicodify, Rwwww, Kimdino, Harthacnut, Itub, Veinor, Crystallina, SmackBot, Emeraldemon, Selfworm, Mjposner, Anarchist42, KnowledgeOfSelf, Gnangarra, Jacek Kendysz, Jagged 85, Aceofspades1217, Lakhim, Gilliam, Hmains, Skizzik, Des1974, RDBrown, JackyR, Thumperward, OrangeDog, Timneu22, SchfiftyThree, Jerome Charles Potts, Octahedron80, Zven, Ken Estabrook, Can't sleep, clown will eat me, Aleksandar Šušnjar, OrphanBot, JonHarder, Rrburke, Addshore, Messybeast, Funky Monkey, Blake-, Sheepdontswim, RJBurkhart, Pilotguy, Spinality, The undertow, Harryboyles, Mouse Nightshirt, Zebbie, John, AmiDaniel, Vgy7ujm, Dejudicibus, SilkTork, Benesch, Shadowlynk, This user has left wikipedia, Coredesat, Mr. Lefty, Ckatz, Ian Dalziel, George The Dragon, SandyGeorgia, AdultSwim, Intranetusa, Condem, Peyre, JeffW, Iridescent, StephenBuxton, Lenoxus, Marysunshine, Tawkerbot2, Chris55, Michaelwilson, JForget, CmdrObot, Kariandelos, CharacterZero, TitusSchleyer, Michal.Pohorelsky, Barnas, Chrishaw, Mblumber, OnPatrol, Myscrnnm, Dancter, Torc2, Jrgetsin, Optimist on the run, Viridae, Kozuch, After Midnight, Omicronpersei8, Niubrad, Satori Son, Malleus Fatuorum, Kubanczyk, Loudsox, Kablammo, Ruddyflipper, Marek69, Humble Scribe, Parsiferon, X201, PaulLambert, The Hybrid, Tree Hugger, Dawnseeker2000, Apantomimehorse, I already forgot, AntiVandalBot, Macmanui, Widefox, Rolgiati, Roundhouse0, Science History, Myanw, JAnDbot, Harryzilber, MER-C, Bronco66, Matthew Fennell, Arch dude, Austinmurphy, Bookinvestor, LittleOldMe, Geniac, Magioladitis, VoABot II, Fusionmix, Hasek is the best, JamesBWatson, Kokin, Ecksemmess, Dulciana, Nikevich, David Eppstein, Glen, Gurko, DerHexer, JaGa, Oicumayberight, MartinBot, Eng.ahmedm, STBot, Jerry teps, Glrx, Maddogprod, Yonaa, Lilac Soul, Artaxiad, TweeterMan, J.delanoy, Jorgenumata, Pharaoh of the Wizards, Rgoodermote, Tom Paine, Wa3frp, Terrek, Uncle Dick, Jerry, Ian.thomson, Celephicus, Mr Rookles, SpigotMap, Lee.crabtree, Gigantic Killerdong, Ohms law, Babedacus, Jozwolf, Martial75, Stolensoul, TraceyR, Wikieditor06, Lights, Caribbean H.Q., VolkovBot, Jeff G., Jennavecia, Philip Trueman, TXiKiBoT, GimmeBot, Davehi1, Bitjungle, Imasleepviking, TedColes, Wpedzich, LeaveSleaves, Jamelan, Softtest123, Enigmaman, Haseo9999, Blinx283, NickdeClaw, Dmcq, Vinhtantran, Sfmammamia, Red, Wjl2, SieBot, Ivan Štambuk, Malcolmxl5, Pakistan566, RJaguar3, Yintan, WRK, Flyer22, Radon210, Darvinkevin, Brian R Hunter, Oxymoron83, AngelOfSadness, Lightmouse, SimonTrew, PbBot, CharlesGillingham, Cyfal, Joao200, ImageRemovalBot, SallyForth123, Tomasz Prochownik, ClueBot, Admiral Norton, Snigbrook, Wikievil666, The Thing That Should Not Be, Plastikspork, Witchwooder, Adrian g. abac, Rilak, Quinxorin, Boing! said Zebedee, Niceguyedc, Namazu-tron, LukeTheSpook, Gradient drift, DragonBot, Tangocz, Eeekster, IamNotU, BOTarate, Thehelpfulone, Blow of Light, Johnuniq, DumZiBoT, Ultima1209, Terry0051, FactChecker1199, Well-rested, Avoided, Mitch Ames, WikHead, SilvonenBot, NellieBly, Galzigler, Alexius08, Noctibus, G7huiben, Docey, Laaknor, Ejosse1, Steven CO2, Midgitman(REAL), Ghettoblaster, Willking1979, DOI bot, DelaneyAdams, Mathew Rammer, Computerhistory, Fieldday-sunday, Download, LinkFA-Bot, LarryJeff, Tide rolls, OlEnglish, Softy, Margin1522, Arxiloxos, Legobot, PlankBot, Luckas-bot, Yobot, Themfromspace, Bunnyhop11, Ptbotgourou, Kilom691, Ron cool1, QueenCake, Bublegun, Iroony, MrBurns, AnomieBOT, Kerred1O1, Rubinbot, Jim1138, Public Kanonkas, Neptune5000, Piano non troppo, Kyrstymoon, Kingpin13, RandomAct, Flewis, Materialscientist, Citation bot, Maxis ftw, Wrelwser43, ArthurBot, DirlBot, Inferno, Lord of Penguins, Encyclopedia Master, Miym, Solphusion, Hpmemproject, Yoganate79, Firdaus065, Shadowjams, Astatine-210, StoneProphet, FrescoBot, Degress, MetaNest, Kwiki, Citation bot 1, Nixiebunny, Pinethicket, 10metreh, Calmer Waters, Skyerise, Xcvista, Ezrdr, MastiBot, Meaghan, Lissajous, Horst-schlaemma, SkyMachine, Cnwilliams, FoxBot, Trappist the monk, SchreyP, FlyTexas, Dalakov, Snareshane, Grammarxxx, Vrenator, Reaper Eternal, Lysander89, Jmarcus1256, DARTH SIDIOUS 2, RjwilmsiBot, Max The Magnificent, Woovee, Rollins83, DASHBot, Jpatros, Haguraa, John of Reading, WikitanvirBot, Racerx11, RA0808, Solarra, Tommy2010, Wikipelli, Werieth, Qwertyrandom, Billy9999, John Cline, Josve05a, Bollyjeff, MigueldelosSantos, Ryan1joseph, H3llBot, Indicer, Gz33, LordJeff, Deutschgirl, Noodleki, Donner60, JoHnNhOeL, Orange Suede Sofa, Gauravkkr, DemonicPartyHat, Whoop whoop pull up, ArsenalTechKB, Rajan2323, Petrb, ClueBot NG, Gameking123, Mohozego, Movses-bot, Deer*lake, Snotbot, Frietjes, Braincricket, O.Koslowski, Csc300c0, 686dosco, Widr, G8yingri, BTR742, Helpful Pixie Bot, Wbm1058, Bibcode Bot, BG19bot, WilliamBrain, MusikAnimal, Ilayaaditya, Min.neel, PwilliamQ99, Klilidiplomus, BattyBot, MilanBgd, Embrittled, Danmoberly, JYBot, FLIPPITY PANTS, Vogone, Lone boatman, LlamaDude78, Graphium, Jamesx12345, Sriharsh1234, MattyPatty33000, Tomonkeys, Faizan, Epicgenius, Acetotyce, Mcioffi, Backendgaming, LudicrousTripe, Comp.arch, Shreyabayari, Asesino6592, Lokoturkey2, Monkbot, Vieque, Powerful786, Bensbens1, Trackteur, Whiteguy510, Johnsoniensis, Yoloswagbossmoney, Evolutionvisions, GeorginaMat, Thatguydude47099, Diran2, SQMeaner and Anonymous: 839

- **Instructions per second** *Source:* http://en.wikipedia.org/wiki/Instructions%20per%20second?oldid=645183850 *Contributors:* Damian Yerrick, The Anome, Heron, Patrick, RTC, Michael Hardy, Ixfd64, Mdebets, Med, Rob Hooft, Wfeidt, Emperorbma, ShaunOfTheLive, Wolfgang Kufner, Furrykef, David Shay, Ed g2s, Shizhao, Dbabbitt, Robbot, ZimZalaBim, DavidCary, Laudaka, Herbee, Thetorpedodog, Nomad, Macrakis, Gzornenplatz, Bobblewik, Chowbok, Andycjp, Bumm13, Huwr, Icairns, Hellisp, Quota, MementoVivere, Lambrinos, ArnoldReinhold, Thomas Willerich, Roo72, ZeroOne, CanisRufus, Alereon, BrokenSegue, Jdabney, Guy Harris, Denoir, Wimvandorst, Gunter, Gene Nygaard, Rzelnik, BerserkerBen, Tabletop, Obersachse, BD2412, Qwertyus, Psm, ZeroUm, StuartBrady, Jidan, Mr.Do!, Borgx, Hede2000, Msikma, Robertvan1, Speedevil, Xidaux, DeadEyeArrow, Poohneat, SmackBot, Bigbluefish, Brianski, Jprg1966, MalafayaBot, Bkehoe, Frap, Jsavit, Fitzhugh, A5b, Alan G. Archer, Ceoil, Insanity13, Asklucas, Wislam, Mgiganteus1, IronGargoyle, Kvng, TerryE, CmdrObot, Jmaynard, Dematt, Naudefj, Kozuch, AstroPig7, PamD, Thijs!bot, Electron9, Kylemcinnes, Arx Fortis, Gjeremy, Fidelfair, FidelFair, CosineKitty, IanOsgood, Xeno, Xangis, Antientropic, User A1, Hbent, Gwern, Jamei, Speck-Made, J.delanoy, Brien86, Alpha43, Jeepday, AlnoktaBOT, Mmu man, Cerebellum, Juliabackhausen, Syokazuliao, Oxymoron83, ClueBot, The Thing That Should Not Be, Lamoonia, Rilak, Fairseeder, PauliKL, DumZiBoT, Zodon, Dsimic, Addbot, Ramu50, Roy Longbottom, Petererr, Leszek Jańczuk, Legobot, Yobot, OrgasGirl, AnomieBOT, M!uqomzXb, Halabeaster54, RibotBOT, Galraedia, ClickRick, IrrtNie, RedBot, SpaceFlight89, Tofutwitch11, MoreNet, Gilly of III, RjwilmsiBot, WikitanvirBot, Efdedent, Dewritech, AvicBot, ZéroBot, Josve05a, ArachanoxReal, MrCrackers, Bamyers99, Sbmeirow, JimOfConcord, Mikhail Ryazanov, ClueBot NG, Linuskardell, Mburkley, Helpful Pixie Bot, Taddybear, BattyBot, Omarsis81, Americanplus, ChrisGualtieri, Oranjelo100, Michał Wierzbicki, Henry stuffedcow and Anonymous: 182

7.7.2 Images

- **File:099-tpm3-sk.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/aa/099-tpm3-sk.jpg *License:* Public domain *Contributors:* Scan made by uploader from copy of Thomson's design sketch for the third tide-predicting machine, 1879-81, as published in Proceedings of the Institution of Civil Engineers, vol.65, 1881 --- too old to be in copyright. *Original artist:* en:J. J. Thomson (died in 1940)
- **File:AKAT-1.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/7e/AKAT-1.JPG *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Topory
- **File:Abacus_6.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/af/Abacus_6.png *License:* Public domain *Contributors:*
- Article for "abacus", 9th edition Encyclopedia Britannica, volume 1 (1875); scanned and uploaded by Malcolm Farmer *Original artist:* Encyclopædia Britannica
- **File:Analog_Computing_Machine_GPN-2000-000354.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/0e/Analog_Computing_Machine_GPN-2000-000354.jpg *License:* Public domain *Contributors:* NIX C1949-24357 *Original artist:* NASA Headquarters - GReatest Images of NASA (NASA-HQ-GRIN)
- **File:AnalyticalMachine_Babbage_London.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/ac/AnalyticalMachine_Babbage_London.jpg *License:* CC BY-SA 2.5 *Contributors:* Own work *Original artist:* Bruno Barral (ByB)
- **File:Atanasoff-Berry_Computer_at_Durhum_Center.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/01/Atanasoff-Berry_Computer_at_Durhum_Center.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* User:Manop
- **File:Beschrijving_van_de_Deltar.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9d/Beschrijving_van_de_Deltar.jpg *License:* Attribution *Contributors:* BeeldbankVenW.nl, Rijkswaterstaat *Original artist:* Henri Cormont
- **File:Bifnordennomenclature.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/42/Bifnordennomenclature.jpg *License:* Public domain *Contributors:* Source: http://www.twinbeech.com/images/bombsight/bifnordennomenclature.jpg *Original artist:* ?
- **File:Colossus.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4b/Colossus.jpg *License:* Public domain *Contributors:* This file is from the collections of The National Archives (United Kingdom), catalogued under document record **FO850/234**. For high quality reproductions of any item from The National Archives collection please contact the image library.
Original artist: Unknown
- **File:ColossusRebuild_12.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/36/ColossusRebuild_12.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* MaltaGC
- **File:Commons-logo.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/4a/Commons-logo.svg *License:* ? *Contributors:* ? *Original artist:* ?
- **File:Curta01.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/5c/Curta01.JPG *License:* CC BY-SA 2.5 *Contributors:* Created this image in Indianapolis, IN *Original artist:* Larry McElhiney
- **File:De_Deltar,_27_januari_1972.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/97/De_Deltar%2C_27_januari_1972.jpg *License:* Attribution *Contributors:* BeeldbankVenW.nl, Rijkswaterstaat *Original artist:* Henri Cormont
- **File:DeflectionAngle.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c1/DeflectionAngle.png *License:* Public domain *Contributors:* Transferred from en.wikipedia to Commons by User:Commonlingua using CommonsHelper. *Original artist:* Ziggle at en.wikipedia
- **File:Difference_engine_plate_1853.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9e/Difference_engine_plate_1853.jpg *License:* Public domain *Contributors:* Google books *Original artist:* Woodcut after a drawing by Benjamin Herschel Babbage
- **File:Drift_Sight_Mk._I_on_DH4.jpeg** *Source:* http://upload.wikimedia.org/wikipedia/en/2/2c/Drift_Sight_Mk._I_on_DH4.jpeg *License:* PD *Contributors:*
Interwar Development of Bombsights on the US Air Force Museum *Original artist:*
U.S. Air Force (more likely the US Army Air Service)
- **File:Early_SSA_accounting_operations.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/f7/Early_SSA_accounting_operations.jpg *License:* Public domain *Contributors:* http://www.ssa.gov/history/acalcs.html *Original artist:* US Social Security Administration
- **File:Eniac.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4e/Eniac.jpg *License:* Public domain *Contributors:* U.S. Army Photo *Original artist:* Unknown
- **File:FiringGeometry.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/1d/FiringGeometry.png *License:* Public domain *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:Sreejithk2000 using CommonsHelper. *Original artist:* Original uploader was Ziggle at en.wikipedia
- **File:Folder_Hexagonal_Icon.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/48/Folder_Hexagonal_Icon.svg *License:* Cc-by-sa-3.0 *Contributors:* ? *Original artist:* ?
- **File:Heathkit_Analog_Computer.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/ac/Heathkit_Analog_Computer.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Swtpc6800 Michael Holley
- **File:IBM-650-panel.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/ad/IBM-650-panel.jpg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:Information_processing_system_(english).svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/38/Information_processing_system_%28english%29.svg *License:* Public domain *Contributors:* Transferred from en.wikipedia; transfer was stated to be made by User:thumperward. *Original artist:* Original uploader was Gradient drift at en.wikipedia
- **File:Intel_8742_153056995.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/64/Intel_8742_153056995.jpg *License:* CC BY-SA 2.0 *Contributors:* http://www.flickr.com/photos/biwook/153056995/ *Original artist:* Ioan Sameli
- **File:Intercept.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/2f/Intercept.png *License:* Public domain *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:Quadell using CommonsHelper. *Original artist:* Original uploader was Ziggle at en.wikipedia

- **File:Internet_map_1024.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/d2/Internet_map_1024.jpg *License:* CC BY 2.5 *Contributors:* Originally from the English Wikipedia; description page is/was here. *Original artist:* The Opte Project
- **File:Magnetic_core.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/51/Magnetic_core.jpg *License:* CC BY 2.5 *Contributors:* ? *Original artist:* ?
- **File:Microelectronics_stub.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c3/Microelectronics_stub.svg *License:* LGPL *Contributors:* Integrated circuit icon.svg**:** *Original artist:* Integrated_circuit_icon.svg: Everaldo Coelho and YellowIcon
- **File:NAMA_Machine_d'Anticythère_1.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/66/NAMA_Machine_d%27Anticyth%C3%A8re_1.jpg *License:* CC BY 2.5 *Contributors:* ? *Original artist:* ?
- **File:Napier'{}s_calculating_tables.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/af/Napier%27s_calculating_tables.JPG *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Kim Traynor
- **File:NewmarkAnalogueComputer.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/61/NewmarkAnalogueComputer.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Kierano
- **File:Os_d'Ishango_IRSNB.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/42/Os_d%27Ishango_IRSNB.JPG *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Ben2
- **File:Pascaline_calculator.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b4/Pascaline_calculator.jpg *License:* Public domain *Contributors:* Downloaded 2008-1-9 from <a data-x-rel='nofollow' class='external text' href='http://books.google.com/books?id=ir00AAAAMAAJ,,&,,pg=PA10'>J. A. V. Turck (1921) *Origin of Modern Calculating Machines*, Western Society of Engineers, Chicago, USA, p.10, fig.2 from Google Books *Original artist:* J. A. V. Turck
- **File:Question_book-new.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/9/99/Question_book-new.svg *License:* Cc-by-sa-3.0 *Contributors:*

  Created from scratch in Adobe Illustrator. Based on Image:Question book.png created by User:Equazcion *Original artist:* Tkgd2007
- **File:SSEM_Manchester_museum_close_up.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/21/SSEM_Manchester_museum_close_up.jpg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Parrot of Doom
- **File:Sliderule_2005.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/17/Sliderule_2005.png *License:* CC-BY-SA-3.0 *Contributors:*
- Sliderule_2005.jpg *Original artist:* Sliderule_2005.jpg: Roger McLassus
- **File:TDC_innerds.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/27/TDC_innerds.JPG *License:* CC BY-SA 3.0 *Contributors:* Own work, photographed by uploader, Samuel Wantman *Original artist:* Sam.
- **File:TDCfullview.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/0a/TDCfullview.jpg *License:* Public domain *Contributors:* Transferred from en.wikipedia; transfer was stated to be made by User:Mieczeslaw. *Original artist:* Original uploader was Ziggle at en.wikipedia
- **File:Transistor-die-KSY34.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e2/Transistor-die-KSY34.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:University_of_Manchester_Atlas,_January_1963.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/d9/University_of_Manchester_Atlas%2C_January_1963.JPG *License:* CC BY 3.0 *Contributors:* email from my father, Iain MacCallum *Original artist:* Iain MacCallum
- **File:Von_Neumann_architecture.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/84/Von_Neumann_architecture.svg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:Wikiversity-logo.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/91/Wikiversity-logo.svg *License:* CC BY-SA 3.0 *Contributors:* Snorky (optimized and cleaned up by verdy_p) *Original artist:* Snorky (optimized and cleaned up by verdy_p)
- **File:Z3_Deutsches_Museum.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4c/Z3_Deutsches_Museum.JPG *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Venusianer at de.wikipedia

7.7.3 Content license