A **supercomputer** is a [computer](https://en.wikipedia.org/wiki/Computer) with a high level of performance as compared to a [general-purpose computer](https://en.wikipedia.org/wiki/General-purpose_computer). The performance of a supercomputer is commonly measured in [floating-point](https://en.wikipedia.org/wiki/Floating-point) operations per second ([FLOPS](https://en.wikipedia.org/wiki/FLOPS)) instead of [million instructions per second](https://en.wikipedia.org/wiki/Million_instructions_per_second) (MIPS). Since 2017, supercomputers have existed which can perform over 1017 FLOPS (a hundred [quadrillion](https://en.wikipedia.org/wiki/Orders_of_magnitude_(numbers)#1015) FLOPS, 100 petaFLOPS or 100 PFLOPS).[[3]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-June_2018-3) For comparison, a desktop computer has performance in the range of hundreds of gigaFLOPS (1011) to tens of teraFLOPS (1013).[[4]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-4)[[5]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-5) Since November 2017, all of the [world's fastest 500 supercomputers](https://en.wikipedia.org/wiki/TOP500) run on [Linux](https://en.wikipedia.org/wiki/Linux)-based operating systems.[[6]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-6) Additional research is being conducted in the United States, the European Union, Taiwan, Japan, and China to build faster, more powerful and technologically superior [exascale supercomputers](https://en.wikipedia.org/wiki/Exascale_computing).[[7]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-7)

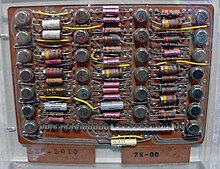
Supercomputers play an important role in the field of [computational science](https://en.wikipedia.org/wiki/Computational_science), and are used for a wide range of computationally intensive tasks in various fields, including [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics), [weather forecasting](https://en.wikipedia.org/wiki/Weather_forecasting), [climate research](https://en.wikipedia.org/wiki/Climate_research), [oil and gas exploration](https://en.wikipedia.org/wiki/Oil_and_gas_exploration), [molecular modeling](https://en.wikipedia.org/wiki/Computational_chemistry) (computing the structures and properties of chemical compounds, biological [macromolecules](https://en.wikipedia.org/wiki/Macromolecules), polymers, and crystals), and physical simulations (such as simulations of the early moments of the universe, airplane and spacecraft [aerodynamics](https://en.wikipedia.org/wiki/Aerodynamics), the detonation of [nuclear weapons](https://en.wikipedia.org/wiki/Nuclear_weapons), and [nuclear fusion](https://en.wikipedia.org/wiki/Nuclear_fusion)). They have been essential in the field of [cryptanalysis](https://en.wikipedia.org/wiki/Cryptanalysis).[[8]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-8)

Supercomputers were introduced in the 1960s, and for several decades the fastest was made by [Seymour Cray](https://en.wikipedia.org/wiki/Seymour_Cray) at [Control Data Corporation](https://en.wikipedia.org/wiki/Control_Data_Corporation) (CDC), [Cray Research](https://en.wikipedia.org/wiki/Cray_Research) and subsequent companies bearing his name or monogram. The first such machines were highly tuned conventional designs that ran more quickly than their more general-purpose contemporaries. Through the decade, increasing amounts of [parallelism](https://en.wikipedia.org/wiki/Parallel_computing) were added, with one to four [processors](https://en.wikipedia.org/wiki/Central_processing_unit) being typical. In the 1970s, [vector processors](https://en.wikipedia.org/wiki/Vector_processor) operating on large arrays of data came to dominate. A notable example is the highly successful [Cray-1](https://en.wikipedia.org/wiki/Cray-1) of 1976. Vector computers remained the dominant design into the 1990s. From then until today, [massively parallel](https://en.wikipedia.org/wiki/Massively_parallel_(computing)) supercomputers with tens of thousands of off-the-shelf processors became the norm.[[9]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Hoffman-9)[[10]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Jouppi-10)

The US has long been the leader in the supercomputer field, first through Cray's almost uninterrupted dominance of the field, and later through a variety of technology companies. Japan made major strides in the field in the 1980s and 90s, with China becoming increasingly active in the field. As of May 2022, the fastest supercomputer on the [TOP500](https://en.wikipedia.org/wiki/TOP500) supercomputer list is [Frontier](https://en.wikipedia.org/wiki/Frontier_(supercomputer)), in the US, with a [LINPACK benchmark](https://en.wikipedia.org/wiki/LINPACK_benchmark) score of 1.102 ExaFlop/s, followed by [Fugaku](https://en.wikipedia.org/wiki/Fugaku_(supercomputer)).[[11]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-11) The US has five of the top 10; China has two; Japan, Finland, and France have one each.[[12]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-top500.org-12) In June 2018, all combined supercomputers on the TOP500 list broke the 1 [exaFLOPS](https://en.wikipedia.org/wiki/Exa-) mark.[[13]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-13)

**History**

Main article: [History of supercomputing](https://en.wikipedia.org/wiki/History_of_supercomputing)

[](https://en.wikipedia.org/wiki/File:IBM_7030_Stretch_circuit_board.jpg)A circuit board from the IBM 7030 [](https://en.wikipedia.org/wiki/File:CDC_6600.jc.jpg)The CDC 6600. Behind the system console are two of the "arms" of the plus-sign shaped cabinet with the covers opened. Each arm of the machine had up to four such racks. On the right is the cooling system. [](https://en.wikipedia.org/wiki/File:Cray-1-deutsches-museum.jpg)A [Cray-1](https://en.wikipedia.org/wiki/Cray-1) preserved at the [Deutsches Museum](https://en.wikipedia.org/wiki/Deutsches_Museum)

In 1960, [UNIVAC](https://en.wikipedia.org/wiki/UNIVAC) built the [Livermore Atomic Research Computer](https://en.wikipedia.org/wiki/UNIVAC_LARC) (LARC), today considered among the first supercomputers, for the US Navy Research and Development Center. It still used high-speed [drum memory](https://en.wikipedia.org/wiki/Drum_memory), rather than the newly emerging [disk drive](https://en.wikipedia.org/wiki/Disk_drive) technology.[[14]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-14) Also, among the first supercomputers was the [IBM 7030 Stretch](https://en.wikipedia.org/wiki/IBM_7030_Stretch). The IBM 7030 was built by IBM for the [Los Alamos National Laboratory](https://en.wikipedia.org/wiki/Los_Alamos_National_Laboratory), which in 1955 had requested a computer 100 times faster than any existing computer. The IBM 7030 used [transistors](https://en.wikipedia.org/wiki/Transistor_computer), magnetic core memory, [pipelined](https://en.wikipedia.org/wiki/Pipeline_(computing)) instructions, prefetched data through a memory controller and included pioneering random access disk drives. The IBM 7030 was completed in 1961 and despite not meeting the challenge of a hundredfold increase in performance, it was purchased by the Los Alamos National Laboratory. Customers in England and France also bought the computer, and it became the basis for the [IBM 7950 Harvest](https://en.wikipedia.org/wiki/IBM_7950_Harvest), a supercomputer built for [cryptanalysis](https://en.wikipedia.org/wiki/Cryptanalysis).[[15]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-15)

The third pioneering supercomputer project in the early 1960s was the [Atlas](https://en.wikipedia.org/wiki/Atlas_(computer)) at the [University of Manchester](https://en.wikipedia.org/wiki/Victoria_University_of_Manchester), built by a team led by [Tom Kilburn](https://en.wikipedia.org/wiki/Tom_Kilburn). He designed the Atlas to have memory space for up to a million words of 48 bits, but because magnetic storage with such a capacity was unaffordable, the actual core memory of the Atlas was only 16,000 words, with a drum providing memory for a further 96,000 words. The Atlas [operating system](https://en.wikipedia.org/wiki/Operating_system) [swapped](https://en.wikipedia.org/wiki/Swapping_(computing)) data in the form of pages between the magnetic core and the drum. The Atlas operating system also introduced [time-sharing](https://en.wikipedia.org/wiki/Time-sharing) to supercomputing, so that more than one program could be executed on the supercomputer at any one time.[[16]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-16) Atlas was a joint venture between [Ferranti](https://en.wikipedia.org/wiki/Ferranti) and [Manchester University](https://en.wikipedia.org/wiki/Manchester_University) and was designed to operate at processing speeds approaching one microsecond per instruction, about one million instructions per second.[[17]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-17)

The [CDC 6600](https://en.wikipedia.org/wiki/CDC_6600), designed by [Seymour Cray](https://en.wikipedia.org/wiki/Seymour_Cray), was finished in 1964 and marked the transition from [germanium](https://en.wikipedia.org/wiki/Germanium) to [silicon](https://en.wikipedia.org/wiki/Silicon) transistors. Silicon transistors could run more quickly and the overheating problem was solved by introducing refrigeration to the supercomputer design.[[18]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-18) Thus, the CDC6600 became the fastest computer in the world. Given that the 6600 outperformed all the other contemporary computers by about 10 times, it was dubbed a *supercomputer* and defined the supercomputing market, when one hundred computers were sold at $8 million each.[[19]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-19)[[20]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Hannan-20)[[21]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-21)[[22]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-22)

Cray left CDC in 1972 to form his own company, [Cray Research](https://en.wikipedia.org/wiki/Cray).[[20]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Hannan-20) Four years after leaving CDC, Cray delivered the 80 MHz [Cray-1](https://en.wikipedia.org/wiki/Cray-1) in 1976, which became one of the most successful supercomputers in history.[[23]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Hill41-23)[[24]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Edwin65-24) The [Cray-2](https://en.wikipedia.org/wiki/Cray-2) was released in 1985. It had eight [central processing units](https://en.wikipedia.org/wiki/Central_processing_unit) (CPUs), [liquid cooling](https://en.wikipedia.org/wiki/Computer_cooling) and the electronics coolant liquid [Fluorinert](https://en.wikipedia.org/wiki/Fluorinert) was pumped through the [supercomputer architecture](https://en.wikipedia.org/wiki/Supercomputer_architecture). It reached 1.9 [gigaFLOPS](https://en.wikipedia.org/wiki/GigaFLOPS), making it the first supercomputer to break the gigaflop barrier.[[25]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-25)

**Massively parallel designs**

Main articles: [Supercomputer architecture](https://en.wikipedia.org/wiki/Supercomputer_architecture) and [Parallel computer hardware](https://en.wikipedia.org/wiki/Parallel_computer_hardware)

[](https://en.wikipedia.org/wiki/File:BlueGeneL_cabinet.jpg)A cabinet of the massively parallel [Blue Gene](https://en.wikipedia.org/wiki/Blue_Gene)/L, showing the stacked [blades](https://en.wikipedia.org/wiki/Blade_server), each holding many processors

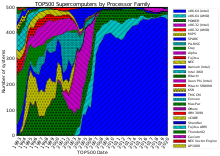
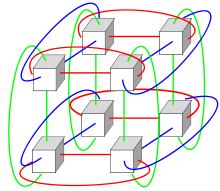
The only computer to seriously challenge the Cray-1's performance in the 1970s was the [ILLIAC IV](https://en.wikipedia.org/wiki/ILLIAC_IV). This machine was the first realized example of a true [massively parallel](https://en.wikipedia.org/wiki/Massively_parallel) computer, in which many processors worked together to solve different parts of a single larger problem. In contrast with the vector systems, which were designed to run a single stream of data as quickly as possible, in this concept, the computer instead feeds separate parts of the data to entirely different processors and then recombines the results. The ILLIAC's design was finalized in 1966 with 256 processors and offer speed up to 1 GFLOPS, compared to the 1970s Cray-1's peak of 250 MFLOPS. However, development problems led to only 64 processors being built, and the system could never operate more quickly than about 200 MFLOPS while being much larger and more complex than the Cray. Another problem was that writing software for the system was difficult, and getting peak performance from it was a matter of serious effort.

But the partial success of the ILLIAC IV was widely seen as pointing the way to the future of supercomputing. Cray argued against this, famously quipping that "If you were plowing a field, which would you rather use? Two strong oxen or 1024 chickens?"[[26]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-26) But by the early 1980s, several teams were working on parallel designs with thousands of processors, notably the [Connection Machine](https://en.wikipedia.org/wiki/Connection_Machine) (CM) that developed from research at [MIT](https://en.wikipedia.org/wiki/MIT). The CM-1 used as many as 65,536 simplified custom [microprocessors](https://en.wikipedia.org/wiki/Microprocessor) connected together in a [network](https://en.wikipedia.org/wiki/Computer_network) to share data. Several updated versions followed; the CM-5 supercomputer is a massively parallel processing computer capable of many billions of arithmetic operations per second.[[27]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-27)

In 1982, [Osaka University](https://en.wikipedia.org/wiki/Osaka_University)'s [LINKS-1 Computer Graphics System](https://en.wikipedia.org/wiki/Supercomputing_in_Japan) used a [massively parallel](https://en.wikipedia.org/wiki/Massively_parallel) processing architecture, with 514 [microprocessors](https://en.wikipedia.org/wiki/Microprocessor), including 257 [Zilog Z8001](https://en.wikipedia.org/wiki/Zilog_Z8000) [control processors](https://en.wikipedia.org/wiki/Central_processing_unit) and 257 [iAPX](https://en.wikipedia.org/wiki/IAPX) [86/20](https://en.wikipedia.org/wiki/IAPX_86) [floating-point processors](https://en.wikipedia.org/wiki/Floating-point_unit). It was mainly used for rendering realistic [3D computer graphics](https://en.wikipedia.org/wiki/3D_computer_graphics).[[28]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-28) Fujitsu's VPP500 from 1992 is unusual since, to achieve higher speeds, its processors used [GaAs](https://en.wikipedia.org/wiki/GaAs), a material normally reserved for microwave applications due to its toxicity.[[29]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-29) [Fujitsu](https://en.wikipedia.org/wiki/Fujitsu)'s [Numerical Wind Tunnel](https://en.wikipedia.org/wiki/Numerical_Wind_Tunnel) supercomputer used 166 vector processors to gain the top spot in 1994 with a peak speed of 1.7 [gigaFLOPS (GFLOPS)](https://en.wikipedia.org/wiki/FLOPS) per processor.[[30]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-30)[[31]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-31) The [Hitachi SR2201](https://en.wikipedia.org/wiki/Hitachi_SR2201) obtained a peak performance of 600 GFLOPS in 1996 by using 2048 processors connected via a fast three-dimensional [crossbar](https://en.wikipedia.org/wiki/Crossbar_switch) network.[[32]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-32)[[33]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-33)[[34]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-34) The [Intel Paragon](https://en.wikipedia.org/wiki/Intel_Paragon) could have 1000 to 4000 [Intel i860](https://en.wikipedia.org/wiki/Intel_i860) processors in various configurations and was ranked the fastest in the world in 1993. The Paragon was a [MIMD](https://en.wikipedia.org/wiki/Multiple_instruction,_multiple_data) machine which connected processors via a high speed two-dimensional mesh, allowing processes to execute on separate nodes, communicating via the [Message Passing Interface](https://en.wikipedia.org/wiki/Message_Passing_Interface).[[35]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-35)

Software development remained a problem, but the CM series sparked off considerable research into this issue. Similar designs using custom hardware were made by many companies, including the [Evans & Sutherland ES-1](https://en.wikipedia.org/wiki/Evans_%26_Sutherland_ES-1), [MasPar](https://en.wikipedia.org/wiki/MasPar), [nCUBE](https://en.wikipedia.org/wiki/NCUBE), [Intel iPSC](https://en.wikipedia.org/wiki/Intel_iPSC) and the [Goodyear MPP](https://en.wikipedia.org/wiki/Goodyear_MPP). But by the mid-1990s, general-purpose CPU performance had improved so much in that a supercomputer could be built using them as the individual processing units, instead of using custom chips. By the turn of the 21st century, designs featuring tens of thousands of commodity CPUs were the norm, with later machines adding [graphic units](https://en.wikipedia.org/wiki/GPGPU) to the mix.[[9]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Hoffman-9)[[10]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Jouppi-10)

In 1998, [David Bader](https://en.wikipedia.org/wiki/David_A._Bader) developed the first [Linux](https://en.wikipedia.org/wiki/Linux) supercomputer using commodity parts.[[36]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-fernbach-36) While at the University of New Mexico, Bader sought to build a supercomputer running Linux using consumer off-the-shelf parts and a high-speed low-latency interconnection network. The prototype utilized an Alta Technologies "AltaCluster" of eight dual, 333 MHz, Intel Pentium II computers running a modified Linux kernel. Bader ported a significant amount of software to provide Linux support for necessary components as well as code from members of the National Computational Science Alliance (NCSA) to ensure interoperability, as none of it had been run on Linux previously.[[37]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-IEEEhistory-37) Using the successful prototype design, he led the development of "RoadRunner," the first Linux supercomputer for open use by the national science and engineering community via the National Science Foundation's National Technology Grid. RoadRunner was put into production use in April 1999. At the time of its deployment, it was considered one of the 100 fastest supercomputers in the world.[[37]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-IEEEhistory-37)[[38]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-AJRoadRunner-38) Though Linux-based clusters using consumer-grade parts, such as [Beowulf](https://en.wikipedia.org/wiki/Beowulf_cluster), existed prior to the development of Bader's prototype and RoadRunner, they lacked the scalability, bandwidth, and parallel computing capabilities to be considered "true" supercomputers.[[37]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-IEEEhistory-37)

[](https://en.wikipedia.org/wiki/File:Processor_families_in_TOP500_supercomputers.svg)The CPU share of [TOP500](https://en.wikipedia.org/wiki/TOP500) [](https://en.wikipedia.org/wiki/File:2x2x2torus.svg)Diagram of a three-dimensional [torus interconnect](https://en.wikipedia.org/wiki/Torus_interconnect) used by systems such as Blue Gene, Cray XT3, etc.

Systems with a massive number of processors generally take one of two paths. In the [grid computing](https://en.wikipedia.org/wiki/Grid_computing) approach, the processing power of many computers, organized as distributed, diverse administrative domains, is opportunistically used whenever a computer is available.[[39]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Prodan-39) In another approach, many processors are used in proximity to each other, e.g. in a [computer cluster](https://en.wikipedia.org/wiki/Computer_cluster). In such a centralized [massively parallel](https://en.wikipedia.org/wiki/Massively_parallel) system the speed and flexibility of the *interconnect* becomes very important and modern supercomputers have used various approaches ranging from enhanced [Infiniband](https://en.wikipedia.org/wiki/Infiniband) systems to three-dimensional [torus interconnects](https://en.wikipedia.org/wiki/Torus_interconnect).[[40]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Bluenight-40)[[41]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-41) The use of [multi-core processors](https://en.wikipedia.org/wiki/Multi-core_processor) combined with centralization is an emerging direction, e.g. as in the [Cyclops64](https://en.wikipedia.org/wiki/Cyclops64) system.[[42]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Cellular_Computer_Architecture_Cyclops64'_2005,_pages_132–143-42)[[43]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Guangming-43)

As the price, performance and [energy efficiency](https://en.wikipedia.org/wiki/Efficient_energy_use) of [general-purpose graphics processing units](https://en.wikipedia.org/wiki/GPGPU) (GPGPUs) have improved, a number of [petaFLOPS](https://en.wikipedia.org/wiki/PetaFLOPS) supercomputers such as [Tianhe-I](https://en.wikipedia.org/wiki/Tianhe-I) and [Nebulae](https://en.wikipedia.org/wiki/Nebulae_(computer)) have started to rely on them.[[44]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-GPGPU-44) However, other systems such as the [K computer](https://en.wikipedia.org/wiki/K_computer) continue to use conventional processors such as [SPARC](https://en.wikipedia.org/wiki/SPARC)-based designs and the overall applicability of [GPGPUs](https://en.wikipedia.org/wiki/GPGPU) in general-purpose high-performance computing applications has been the subject of debate, in that while a GPGPU may be tuned to score well on specific benchmarks, its overall applicability to everyday algorithms may be limited unless significant effort is spent to tune the application to it.[[45]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-HansH-45) However, GPUs are gaining ground, and in 2012 the [Jaguar](https://en.wikipedia.org/wiki/Jaguar_supercomputer) supercomputer was transformed into [Titan](https://en.wikipedia.org/wiki/Titan_(supercomputer)) by retrofitting CPUs with GPUs.[[46]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-PC-46)[[47]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-47)[[48]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-TitanReg-48)

High-performance computers have an expected life cycle of about three years before requiring an upgrade.[[49]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-49) The [Gyoukou](https://en.wikipedia.org/wiki/Gyoukou) supercomputer is unique in that it uses both a massively parallel design and [liquid immersion cooling](https://en.wikipedia.org/wiki/Server_immersion_cooling).

**Special purpose supercomputers**

A number of special-purpose systems have been designed, dedicated to a single problem. This allows the use of specially programmed [FPGA](https://en.wikipedia.org/wiki/Field-programmable_gate_array) chips or even custom [ASICs](https://en.wikipedia.org/wiki/Application-specific_integrated_circuit), allowing better price/performance ratios by sacrificing generality. Examples of special-purpose supercomputers include [Belle](https://en.wikipedia.org/wiki/Belle_(chess_machine)),[[50]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-50) [Deep Blue](https://en.wikipedia.org/wiki/Deep_Blue_(chess_computer)),[[51]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-51) and [Hydra](https://en.wikipedia.org/wiki/Hydra_(chess))[[52]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-52) for playing [chess](https://en.wikipedia.org/wiki/Chess), [Gravity Pipe](https://en.wikipedia.org/wiki/Gravity_Pipe) for astrophysics,[[53]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-53) [MDGRAPE-3](https://en.wikipedia.org/wiki/MDGRAPE-3) for protein structure prediction and molecular dynamics,[[54]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-54) and [Deep Crack](https://en.wikipedia.org/wiki/Deep_Crack) for breaking the [DES](https://en.wikipedia.org/wiki/Data_Encryption_Standard) [cipher](https://en.wikipedia.org/wiki/Cipher).[[55]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-55)

**Energy usage and heat management**

See also: [Computer cooling](https://en.wikipedia.org/wiki/Computer_cooling) and [Green500](https://en.wikipedia.org/wiki/Green500)

[](https://en.wikipedia.org/wiki/File:Summit_(supercomputer).jpg)The [Summit](https://en.wikipedia.org/wiki/Summit_(supercomputer)) supercomputer was as of November 2018 the fastest supercomputer in the world.[[56]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-nytimes-56) With a measured power efficiency of 14.668 GFlops/watt it is also the third most energy efficient in the world.[[57]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-greenlistjune2018-57)

Throughout the decades, the management of [heat density](https://en.wikipedia.org/wiki/Heat_density) has remained a key issue for most centralized supercomputers.[[58]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-TH1-58)[[59]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Charley-59)[[60]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Rupak-60) The large amount of heat generated by a system may also have other effects, e.g. reducing the lifetime of other system components.[[61]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Huang313-61) There have been diverse approaches to heat management, from pumping [Fluorinert](https://en.wikipedia.org/wiki/Fluorinert) through the system, to a hybrid liquid-air cooling system or air cooling with normal [air conditioning](https://en.wikipedia.org/wiki/Air_conditioning) temperatures.[[62]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Tokhi-62)[[63]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-sysx-63) A typical supercomputer consumes large amounts of electrical power, almost all of which is converted into heat, requiring cooling. For example, [Tianhe-1A](https://en.wikipedia.org/wiki/Tianhe-1A) consumes 4.04 [megawatts](https://en.wikipedia.org/wiki/Megawatt) (MW) of electricity.[[64]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-64) The cost to power and cool the system can be significant, e.g. 4 MW at $0.10/kWh is $400 an hour or about $3.5 million per year.

[](https://en.wikipedia.org/wiki/File:IBM_HS20_blade_server.jpg)An [IBM HS20](https://en.wikipedia.org/wiki/IBM_BladeCenter#HS20) [blade](https://en.wikipedia.org/wiki/Blade_server)

Heat management is a major issue in complex electronic devices and affects powerful computer systems in various ways.[[65]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Spectrum-65) The [thermal design power](https://en.wikipedia.org/wiki/Thermal_design_power) and [CPU power dissipation](https://en.wikipedia.org/wiki/CPU_power_dissipation) issues in supercomputing surpass those of traditional [computer cooling](https://en.wikipedia.org/wiki/Computer_cooling) technologies. The supercomputing awards for [green computing](https://en.wikipedia.org/wiki/Green_computing) reflect this issue.[[66]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-66)[[67]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-67)[[68]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-WuFeng-68)

The packing of thousands of processors together inevitably generates significant amounts of [heat density](https://en.wikipedia.org/wiki/Heat_density) that need to be dealt with. The [Cray-2](https://en.wikipedia.org/wiki/Cray-2) was [liquid cooled](https://en.wikipedia.org/wiki/Computer_cooling), and used a [Fluorinert](https://en.wikipedia.org/wiki/Fluorinert) "cooling waterfall" which was forced through the modules under pressure.[[62]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Tokhi-62) However, the submerged liquid cooling approach was not practical for the multi-cabinet systems based on off-the-shelf processors, and in [System X](https://en.wikipedia.org/wiki/System_X_(supercomputer)) a special cooling system that combined air conditioning with liquid cooling was developed in conjunction with the [Liebert company](https://en.wikipedia.org/wiki/Liebert_(company)).[[63]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-sysx-63)

In the [Blue Gene](https://en.wikipedia.org/wiki/Blue_Gene) system, IBM deliberately used low power processors to deal with heat density.[[69]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-TheRegSC10-69) The IBM [Power 775](https://en.wikipedia.org/wiki/Power_775), released in 2011, has closely packed elements that require water cooling.[[70]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-70) The IBM [Aquasar](https://en.wikipedia.org/wiki/Aquasar) system uses hot water cooling to achieve energy efficiency, the water being used to heat buildings as well.[[71]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-71)[[72]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-72)

The energy efficiency of computer systems is generally measured in terms of "[FLOPS per watt](https://en.wikipedia.org/wiki/FLOPS_per_watt)". In 2008, [Roadrunner](https://en.wikipedia.org/wiki/Roadrunner_(supercomputer)) by [IBM](https://en.wikipedia.org/wiki/IBM) operated at 3.76 [MFLOPS/W](https://en.wikipedia.org/wiki/Performance_per_watt).[[73]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-73)[[74]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-74) In November 2010, the [Blue Gene/Q](https://en.wikipedia.org/wiki/IBM_Blue_Gene#Blue_Gene/Q) reached 1,684 MFLOPS/W[[75]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-75)[[76]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-76) and in June 2011 the top two spots on the [Green 500](https://en.wikipedia.org/wiki/Green_500) list were occupied by [Blue Gene](https://en.wikipedia.org/wiki/Blue_Gene) machines in New York (one achieving 2097 MFLOPS/W) with the [DEGIMA cluster](https://en.wikipedia.org/wiki/DEGIMA_(computer_cluster)) in Nagasaki placing third with 1375 MFLOPS/W.[[77]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-77)

Because copper wires can transfer energy into a supercomputer with much higher power densities than forced air or circulating refrigerants can remove [waste heat](https://en.wikipedia.org/wiki/Waste_heat),[[78]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-78) the ability of the cooling systems to remove waste heat is a limiting factor.[[79]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-79)[[80]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-80) As of 2015, many existing supercomputers have more infrastructure capacity than the actual peak demand of the machine – designers generally conservatively design the power and cooling infrastructure to handle more than the theoretical peak electrical power consumed by the supercomputer. Designs for future supercomputers are power-limited – the [thermal design power](https://en.wikipedia.org/wiki/Thermal_design_power) of the supercomputer as a whole, the amount that the power and cooling infrastructure can handle, is somewhat more than the expected normal power consumption, but less than the theoretical peak power consumption of the electronic hardware.[[81]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-81)

**Software and system management**

**Operating systems**

Main article: [Supercomputer operating systems](https://en.wikipedia.org/wiki/Supercomputer_operating_systems)

Since the end of the 20th century, [supercomputer operating systems](https://en.wikipedia.org/wiki/Supercomputer_operating_systems) have undergone major transformations, based on the changes in [supercomputer architecture](https://en.wikipedia.org/wiki/Supercomputer_architecture).[[82]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Padua426-82) While early operating systems were custom tailored to each supercomputer to gain speed, the trend has been to move away from in-house operating systems to the adaptation of generic software such as [Linux](https://en.wikipedia.org/wiki/Linux).[[83]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-MacKenzie-83)

Since modern [massively parallel](https://en.wikipedia.org/wiki/Massively_parallel) supercomputers typically separate computations from other services by using multiple types of [nodes](https://en.wikipedia.org/wiki/Locale_(computer_hardware)), they usually run different operating systems on different nodes, e.g. using a small and efficient [lightweight kernel](https://en.wikipedia.org/wiki/Lightweight_Kernel_Operating_System) such as [CNK](https://en.wikipedia.org/wiki/CNK_operating_system) or [CNL](https://en.wikipedia.org/wiki/Compute_Node_Linux) on compute nodes, but a larger system such as a [Linux](https://en.wikipedia.org/wiki/Linux)-derivative on server and [I/O](https://en.wikipedia.org/wiki/I/O) nodes.[[84]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-EuroPar2004-84)[[85]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-EuroPar2006-85)[[86]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Alam-86)

While in a traditional multi-user computer system [job scheduling](https://en.wikipedia.org/wiki/Job_scheduling) is, in effect, a [tasking](https://en.wikipedia.org/wiki/Task_scheduling) problem for processing and peripheral resources, in a massively parallel system, the job management system needs to manage the allocation of both computational and communication resources, as well as gracefully deal with inevitable hardware failures when tens of thousands of processors are present.[[87]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Yariv-87)

Although most modern supercomputers use [Linux](https://en.wikipedia.org/wiki/Linux)-based operating systems, each manufacturer has its own specific Linux-derivative, and no industry standard exists, partly due to the fact that the differences in hardware architectures require changes to optimize the operating system to each hardware design.[[82]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Padua426-82)[[88]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-88)

**Software tools and message passing**

Main article: [Message passing in computer clusters](https://en.wikipedia.org/wiki/Message_passing_in_computer_clusters)

See also: [Parallel computing](https://en.wikipedia.org/wiki/Parallel_computing) and [Parallel programming model](https://en.wikipedia.org/wiki/Parallel_programming_model)

[](https://en.wikipedia.org/wiki/File:Wide-angle_view_of_the_ALMA_correlator.jpg)Wide-angle view of the [ALMA](https://en.wikipedia.org/wiki/Atacama_Large_Millimeter_Array) correlator[[89]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-89)

The parallel architectures of supercomputers often dictate the use of special programming techniques to exploit their speed. Software tools for distributed processing include standard [APIs](https://en.wikipedia.org/wiki/Application_programming_interface) such as [MPI](https://en.wikipedia.org/wiki/Message_Passing_Interface)[[90]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-90) and [PVM](https://en.wikipedia.org/wiki/Parallel_Virtual_Machine), [VTL](https://en.wikipedia.org/wiki/Virtual_tape_library), and [open source](https://en.wikipedia.org/wiki/Open-source_software) software such as [Beowulf](https://en.wikipedia.org/wiki/Beowulf_(computing)).

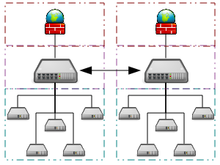
In the most common scenario, environments such as [PVM](https://en.wikipedia.org/wiki/Parallel_Virtual_Machine) and [MPI](https://en.wikipedia.org/wiki/Message_Passing_Interface) for loosely connected clusters and [OpenMP](https://en.wikipedia.org/wiki/OpenMP) for tightly coordinated shared memory machines are used. Significant effort is required to optimize an algorithm for the interconnect characteristics of the machine it will be run on; the aim is to prevent any of the CPUs from wasting time waiting on data from other nodes. [GPGPUs](https://en.wikipedia.org/wiki/GPGPU) have hundreds of processor cores and are programmed using programming models such as [CUDA](https://en.wikipedia.org/wiki/CUDA) or [OpenCL](https://en.wikipedia.org/wiki/OpenCL).

Moreover, it is quite difficult to debug and test parallel programs. [Special techniques](https://en.wikipedia.org/wiki/Testing_high-performance_computing_applications) need to be used for testing and debugging such applications.

**Distributed supercomputing**

**Opportunistic approaches**

Main article: [Grid computing](https://en.wikipedia.org/wiki/Grid_computing)

[](https://en.wikipedia.org/wiki/File:ArchitectureCloudLinksSameSite.png)Example architecture of a [grid computing](https://en.wikipedia.org/wiki/Grid_computing) system connecting many personal computers over the internet

Opportunistic supercomputing is a form of networked [grid computing](https://en.wikipedia.org/wiki/Grid_computing) whereby a "super virtual computer" of many [loosely coupled](https://en.wikipedia.org/wiki/Loose_coupling) volunteer computing machines performs very large computing tasks. Grid computing has been applied to a number of large-scale [embarrassingly parallel](https://en.wikipedia.org/wiki/Embarrassingly_parallel) problems that require supercomputing performance scales. However, basic grid and [cloud computing](https://en.wikipedia.org/wiki/Cloud_computing) approaches that rely on [volunteer computing](https://en.wikipedia.org/wiki/Volunteer_computing) cannot handle traditional supercomputing tasks such as fluid dynamic simulations.[[91]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-91)

The fastest grid computing system is the [volunteer computing project](https://en.wikipedia.org/wiki/List_of_volunteer_computing_projects) [Folding@home](https://en.wikipedia.org/wiki/Folding@home) (F@h). As of April 2020, F@h reported 2.5 exaFLOPS of [x86](https://en.wikipedia.org/wiki/X86) processing power. Of this, over 100 PFLOPS are contributed by clients running on various GPUs, and the rest from various CPU systems.[[92]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-92)

The [Berkeley Open Infrastructure for Network Computing](https://en.wikipedia.org/wiki/Berkeley_Open_Infrastructure_for_Network_Computing) (BOINC) platform hosts a number of volunteer computing projects. As of February 2017, BOINC recorded a processing power of over 166 petaFLOPS through over 762 thousand active Computers (Hosts) on the network.[[93]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-93)

As of October 2016, [Great Internet Mersenne Prime Search](https://en.wikipedia.org/wiki/Great_Internet_Mersenne_Prime_Search)'s (GIMPS) distributed [Mersenne Prime](https://en.wikipedia.org/wiki/Mersenne_Prime) search achieved about 0.313 PFLOPS through over 1.3 million computers.[[94]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-94) The PrimeNet server has supported GIMPS's grid computing approach, one of the earliest volunteer computing projects, since 1997.

**Quasi-opportunistic approaches**

Main article: [Quasi-opportunistic supercomputing](https://en.wikipedia.org/wiki/Quasi-opportunistic_supercomputing)

Quasi-opportunistic supercomputing is a form of [distributed computing](https://en.wikipedia.org/wiki/Distributed_computing) whereby the "super virtual computer" of many networked geographically disperse computers performs computing tasks that demand huge processing power.[[95]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Kravtsov-95) Quasi-opportunistic supercomputing aims to provide a higher quality of service than [opportunistic grid computing](https://en.wikipedia.org/wiki/Grid_computing) by achieving more control over the assignment of tasks to distributed resources and the use of intelligence about the availability and reliability of individual systems within the supercomputing network. However, quasi-opportunistic distributed execution of demanding parallel computing software in grids should be achieved through the implementation of grid-wise allocation agreements, co-allocation subsystems, communication topology-aware allocation mechanisms, fault tolerant message passing libraries and data pre-conditioning.[[95]](https://en.wikipedia.org/wiki/Supercomputer#cite_note-Kravtsov-95)