# El Capitan: A Brief Analysis of the World's Fastest Supercomputer

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**Abstract.** This report conducts an analysis of El Capitan, the current number one supercomputer according to the latest TOP500 rankings. The analysis examines El Capitan's hardware architecture, power requirements, network infrastructure, and operating system. Additionally, a variety of performance metrics are discussed including HPL, BFS, and HPCG benchmarks. Finally, we explore the primary use of El Capitan and applications developed or optimized specifically for it. The report provides an overview of the system's capabilities, design innovations, and scientific applications that demonstrate how exascale computing advances for nuclear simulations and science behind the task.

## 1 Introduction

El Capitan was proposed in 2019 to be the first exascale computer (capable of more than 1 quintillion floating point operations per second) for the National Nuclear Security Administration (NNSA), hosted at Lawrence Livermore National Laboratory (LLNL). It was proposed as a way to run 3D simulations of nuclear weapons and explosions constantly instead of 2D simulations periodically (the current setup) and keep track of the United States' nuclear stockpile. It was part of the CORAL-2 program, a joint effort with the Department of Energy to procure 3 exascale systems for $1.8 billion. [1]

By June 2022, 3 prototypes for El Capitan (rzVernal, Tioga, and Tenaya) debuted in the top 200 of the TOP500 list (a list of the top supercomputers in the world). [2] In November 2024, El Capitan went live and immediately debuted at the top of the TOP500 list, pushing the other exascale computers from the CORAL-2 program (Frontier and Aurora) down to number 2 and number 3. It has maintained its reign ever since. [3]

## 2 Architecture

### 2.1 Processing Units

El Capitan's design centers around Accelerated Processing Units (APUs). An APU integrates both central processing units (CPUs) and graphics processing units (GPUs) onto a single chip, combining two traditionally separate types of processors into one package.

A CPU serves as the computer's primary brain, designed for sequential processing and complex decision making. CPUs excel at tasks requiring logic, branching operations, and managing the overall system. They typically contain a small number of very powerful cores. Cores are the smallest physical processing unit that can independently execute instructions and there are usually between 4 and 64 in high-performance systems.

In contrast, a GPU was originally designed to render images and video by performing thousands of simple calculations simultaneously. Modern GPUs have evolved into massively parallel processors containing thousands of smaller, simpler cores that can work together on large-scale computational problems. While each individual GPU core is less sophisticated than a CPU core, they excel (collectively) when tackling problems that can be broken down into many smaller, parallel tasks.

El Capitan employs a total of 11,039,616 combined CPU and GPU cores distributed across its architecture. This processing power comes from 43,808 AMD fourth-generation EPYC ”Genoa” processors, each containing 24 cores running at 1.8 gigahertz, contributing 1,051,392 CPU cores to the system. These traditional processors handle the memory management, and sequential operations that keep the supercomputer functioning.

The bulk of El Capitan’s computational power, however, comes from 43,808 AMD Instinct MI300A GPUs. Each MI300A contains 228 compute units, and these 43,808 GPUs collectively provide 9,988,224 compute units. Within each compute unit are multiple stream processors ( the units that perform individual calculations). Each MI300A houses 14,592 stream processors, resulting in a total of 639,246,336 stream processors across the entire system.

The MI300A represents AMD’s most advanced APU design, combining 24 Zen4-based CPU cores with CDNA3-based GPU architecture. This integration means that CPU and GPU components share the same physical substrate and can communicate with minimal latency. Each MI300A also includes 128 gigabytes of HBM3 (High Bandwidth Memory), an ultra-fast memory technology that provides both CPU and GPU components with shared access to data, eliminating most of the problems from transferring information between separate CPU and GPU memory pools. Collectively, El Capitan’s memory system provides 5.4 petabytes of total memory capacity, equivalent to storing approximately 1.4 million high-definition movies.

### 2.2 Power Consumption

El Capitan’s immense computational power comes with equally substantial energy requirements, consuming 29,581 kilowatts of electrical power during operation. To put this figure in perspective, this is enough electricity to support more than 2,700 average American homes simultaneously for a year. Despite this El Capitan is only 7500 square feet, the size of one mansion. [5][6][7]

This power consumption reflects the fundamental challenge of exascale computing: each of those millions of processing cores requires electricity to function, and when operating at peak performance, El Capitan consumes as much power as a small city. The 29,581 kW figure represents the maximum power the system draws when all processing units are actively computing, including not only the processors themselves but also the extensive cooling infrastructure required to remove the heat generated by such intensive computational work. El Capitan requires 28,000 tons of liquid cooling, which is enough for over 5000 homes. [7]

El Capitan is predictably among the most energy-intensive machines ever built but despite this massive power draw, it achieves remarkable energy efficiency relative to its computational output, performing approximately 58.89 gigaflops per watt. This initially placed it at number 18 on the Green500 list (a list of the most efficient super computers) in November 2025 but it dropped to 25 in June 2025. [8][9]

### 2.3 Network Infrastructure and Operating System

Connecting El Capitan’s 43,808 processing nodes to form one computer requires some sort of glue. In supercomputing, the network interconnect serves as the system’s circulatory system, enabling the millions of processing cores to communicate, share data, and coordinate their work on computational problems. Without a method for high-speed communication, the individual processing units would remain isolated, unable to tackle problems larger than what a single node could handle.

El Capitan (like the other computers created for (CORAL-2) uses the Cray Slingshot-11 interconnect. Slingshot builds upon Ethernet (the same networking protocol used in everyday computer networks) but extends it far beyond standard capabilities to meet the demanding requirements of exascale computing. The system operates at 200 gigabits per second, providing each node with a large bandwidth for data exchange. This is a great improvement over previous network interconnects as Slingshot-11 introduced 200-gigabit network interface cards, replacing previous ConnectX-5 cards and doubling the injection bandwidth compared to earlier generations.

The architecture utilizes 64-port switches that create a high-bandwidth mesh allowing any node to communicate efficiently with any other node in the system. A critical innovation in Slingshot-11 is its implementation of HPC Ethernet protocol end-to-end, extending specialized high-performance computing network protocols directly to the compute nodes rather than requiring switches to translate between standard Ethernet and HPC-optimized protocols. This eliminates translation overhead and reduces latency, enabling faster communication between processing units during computation. [10]

To manage it's hardware, El Capitan runs HPE Cray Operating System, a specialized software suite engineered specifically for large-scale high-performance computing. Built upon SUSE Enterprise Linux, HPE Cray OS uses the standard Linux foundation but adds optimizations designed to maximize performance, reliability, and scalability.

The operating system has a few differences from conventional computing environments. CPU assignment functionality dedicates specific processor cores exclusively to applications while constraining operating system operations to designated cores, eliminating computational noise that could interfere with calculations. The system supports enhanced memory management through extra huge page sizes, reducing memory access latency by minimizing address translation overhead.

HPE Cray OS also provides advanced inter-process communication capabilities through XPMEM technology, enabling efficient memory sharing between processes. Power management features allow fine-grained monitoring and control of energy consumption, while its debugging capabilities extend beyond standard Linux tools to support the challenges of managing diskless compute nodes and huge memory configurations across thousands of nodes simultaneously. The operating system also includes support for high-performance file systems and provides scalable data access through virtualization services, ensuring the computational power can be fed with data from storage systems. [11]

## 3 Performance

There are several metrics used to measure the performance of super computers. El Capitan passes the vast majority of the various tests available.

### 3.1 Rpeak (Peak Performance)

This represents the theoretical maximum computational throughput a system could achieve under perfect conditions. El Capitan's Rpeak of 2,746.38 teraflops means that if every processing core operated simultaneously at maximum efficiency without any overhead from communication, memory access, or coordination, the system could theoretically perform 2.746 exaflops per second. This figure serves as the upper bound of what is mathematically possible given the hardware specifications, assuming ideal conditions that rarely exist in practice.

### 3.2 Rmax (Maximum Achieved Performance)

This measures the actual performance achieved on a standardized benchmark test. El Capitan's Rmax of 1,742.00 teraflops represents the real-world performance achieved on the High Performance Linpack benchmark, which solves a dense system of linear equations. This is the figure used for TOP500 rankings (where El Capitan is number one) and represents what the system can actually deliver when running optimized software under controlled conditions. [12]

### 3.3 Linpack Efficiency (HPL)

This calculates the percentage of theoretical peak performance that a system actually achieves, providing insight into how well the hardware and software work together. El Capitan's Linpack efficiency of 63.43% means it achieves roughly two-thirds of its theoretical maximum performance. This efficiency ratio reflects the practical challenges of coordinating millions of processing cores, managing memory access, and handling communication overhead. A 63% efficiency is considered quite good for an exascale system, as the complexity of coordination increases dramatically with scale.

### 3.4 High Performance Conjugate Gradients (HPCG)

This presents a different computational challenge that better reflects many real-world scientific applications. Unlike the dense matrix operations tested by Linpack, HPCG measures performance on sparse matrix computations, vector operations, and iterative solvers that are common in engineering simulations and scientific modeling. El Capitan currently holds the number one position on the HPCG benchmark with a performance of 17.41 petaflops per second.

The HPCG benchmark evaluates several other critical operations including vector updates, global dot products, local symmetric Gauss-Seidel smoothing, and sparse triangular solvers. These operations are integrated within a multigrid preconditioned conjugate gradient algorithm that exercises computational kernels across nested sets of coarse grids. The reference implementation utilizes C++ with MPI (Message Passing Interface) for inter-node communication and OpenMP for shared-memory parallelization within nodes, creating what we would argue is a more comprehensive test of the system's ability to handle the complex communication and computation patterns found in real scientific applications than Linpack Efficiency. [13]

### 3.5 Breadth-First Search Graph Traversal (BFS GTEPS)

This measures a system's ability to process graph algorithms, which are increasingly important for data analytics, social network analysis, and certain types of scientific modeling. Measured in billions of traversed edges per second (GTEPS), this benchmark evaluates how efficiently a system can navigate large, irregular data structures. El Capitan has not yet appeared on the Graph500 list that ranks BFS performance, though the other exascale systems from CORAL-2 are charting. Aurora currently ranks fourth while Frontier holds the sixth position. The lack of appearance could mean they have yet to provide submissions or that optimizing El Capitan's software stack for graph algorithms remains an area for future development. [14]

Below are two tables displaying information about the Top 10 systems of the Graph500 list with information available to the public.

| System | Rpeak Pflops/s | Rmax Pflops/s | Linpack % | HPCG Tflops/s |
|---|---|---|---|---|
| 1. Fugaku | 537.21 | 442.01 | 82.28 | 16,004.5 |
| 4. Aurora | 1,980.01 | 1,012.00 | 51.11 | 5,612.6 |
| 5. EOS NVIDIA DGX SUPERPOD | 188.65 | 121.40 | 64.35 | N/A |
| 6. Frontier | 2,055.72 | 1,353.00 | 65.82 | 14,054.0 |
| 8. Sunway TaihuLight | 125.44 | 93.01 | 74.14 | N/A |
| 9. Wisteria/BDEC-01 (Odyssey) | 25.95 | 22.12 | 85.24 | 817.577 |
| 10. MareNostrum 5 ACC | 249.44 | 175.30 | 70.28 | 1,146.98 |
| 11. TOKI-SORA | 19.46 | 16.59 | 85.25 | 614.224 |
| 15. SuperMUC-NG | 26.87 | 19.48 | 72.50 | 207.844 |
| 16. Lise | 8.93 | 6.05 | 67.75 | N/A |

Table 1: Table 1 showcases the HPL and HPCG of the Top 10 systems on the Graph500 list with information publicly available. N/A means that metric is not published for public viewing.

| System | Top500 | Cores | Network | Power kW |
|---|---|---|---|---|
| Fugaku | 7 | 7,630,848 | Tofu interconnect D | 29,899.23 |
| Aurora | 3 | 9,264,128 | Slingshot-11 | 38,698.36 |
| EOS NVIDIA DGX SUPERPOD | 16 | 485,888 | Infiniband NDR400 | N/A |
| Frontier | 2 | 9,066,176 | Slingshot-11 | 24,607.00 |
| Sunway TaihuLight | 21 | 10,649,600 | Sunway | 15,371.00 |
| Wisteria/BDEC-01 (Odyssey) | 73 | 368,640 | Tofu interconnect D | 1,468.00 |
| MareNostrum 5 ACC | 14 | 663,040 | Infiniband NDR | 4,158.90 |
| TOKI-SORA | 96 | 276,480 | Tofu interconnect D | N/A |
| SuperMUC-NG | 81 | 305,856 | Intel Omni-Path | N/A |
| Lise | 215 | 121,920 | Intel Omni-Path | N/A |

Table 2: Table 2 showcases the cores, network, power and Top500 rank of the Top 10 systems on the Graph500 list with information publicly available. N/A means that metric is not published for public viewing.

## 4 Applications

As El Capitan was created with one specific purpose in mind (to simulate explosions from the United States' aging pile of nuclear weapons), there have been several applications designed and/or optimized to aid it in this task.

### 4.1 ICECap (Inertial Confinement on El Capitan)

ICECap is a fusion design optimization framework that combines artificial intelligence workflows with exascale multiphysics simulations. It integrates machine learning algorithms with experimental data from the National Ignition Facility to predict and optimize inertial confinement fusion designs. ICECap leverages multiple GPU-optimized physics codes including MARBL and HYDRA, along with the Merlin workflow system for large-scale machine learning operations. The modular design allows researchers to explore large parameter spaces for fusion experiments while maintaining impressive computational fidelity. ICECap is optimally suited for El Capitan because it requires both the massive parallel processing power for physics simulations and the integrated AI capabilities enabled by the AMD MI300A's unified CPU-GPU architecture, allowing seamless transitions between simulation and machine learning tasks within the same computational framework. [15]

### 4.2 MARBL (Multi-physics Arbitrary Lagrangian-Eulerian code)

MARBL serves as El Capitan's primary multiphysics simulation engine, specifically redesigned to exploit the system's APU architecture. This code simulates complex phenomena including radiation-hydrodynamics, thermonuclear burn processes, and high-energy-density physics crucial for both fusion research and stockpile stewardship missions. MARBL incorporates advanced numerical methods for solving coupled partial differential equations across multiple physics domains, utilizing high-order finite element discretizations on moving meshes. The code has been optimized for GPU acceleration using LLNL's RAJA Portability Suite, enabling efficient execution across different hardware architectures. MARBL represents an optimal choice for El Capitan because its computational patterns (involving sparse matrix operations, irregular memory access, and complex physics coupling) directly leverage the strengths of a system that scores high on the Top500 which is calculated based off sparse matrix operations. [16]

### 4.3 HYDRA

Hydra functions as the principal code for two and three-dimensional inertial confinement fusion design and analysis, serving as a cornerstone application for El Capitan's nuclear security mission. This simulation package models the physics of ICF experiments, including laser-target interactions, hydrodynamic instabilities, and energy transport processes necessary for both understanding weapons physics and fusion energy development. HYDRA uses arbitrary Lagrangian-Eulerian fluid dynamics, radiation transport, and equation-of-state models necessary for high-fidelity simulations of extreme physical conditions. The code has undergone significant modernization to take advantage of GPU acceleration and supports automated workflows for design optimization studies. HYDRA is ideally suited for El Capitan because ICF simulations demand enormous computational resources for capturing multi-scale physics phenomena, while the APU architecture enables efficient coupling between the complex algorithmic components and the massive data movement required for these simulations. [17]

## 5 Conclusion

El Capitan's position as the world's fastest supercomputer demonstrates the successful integration of AMD's MI300A APU architecture with exascale computing requirements, achieving 1.742 exaflops performance while maintaining 63.43% Linpack efficiency and notable energy efficiency at 58.89 gigaflops per watt. The system's applications, such as ICECap for AI-powered fusion design, MARBL for multiphysics simulations, and HYDRA for inertial confinement fusion modeling, show how the integrated CPU-GPU architecture and 5.4 petabytes of memory enable advanced scientific computing for national security missions.

The 63.43% efficiency indicates that El Capitan utilizes roughly two-thirds of its theoretical computational resources, which is typical for large-scale systems where coordination overhead increases with size (smaller machines often achieve higher efficiency percentages), but El Capitan compensates through its exceptional performance on dense and sparse linear algebra operations, as evidenced by its dominance in both HPL and HPCG benchmarks that heavily involve matrix and vector calculations. However, the system's absence from Graph500 rankings suggests potential limitations in graph traversal algorithms, which require different computational patterns and memory access strategies that may not align as well with El Capitan's architecture.

## 6 References

[1] Trader, Tiffany. "Cray Wins NNSA-Livermore 'El Capitan' Exascale Contract." *HPC Wire*, 13 Aug. 2019, https://www.hpcwire.com/2019/08/13/cray-wins-nnsa-livermore-el-capitan-exascale-award/.

[2] Klotz, Aaron. "Trio of Prototype AMD-Based El Capitan Supercomputers Already Rank in Top 200." *Tom's Hardware*, 3 Jun. 2022, https://www.tomshardware.com/news/testedbed-el-captain-ranks-top-200-worlds-fastest-supercomputers.

[3] Afifi-Sabet, Keumars . "World's Fastest Supercomputer 'El Capitan' Goes Online — It Will Be Used to Secure the US Nuclear Stockpile and in Other Classified Research." *Space*, 9 Feb. 2025, https://www.space.com/space-exploration/tech/worlds-fastest-supercomputer-el-capitan-goes-online-it-will-be-used-to-secure-the-us-nuclear-stockpile-and-in-other-classified-research.

[4] Sinha, Sujita. "US: World's Fastest Supercomputer with 11 Million Cores Powers up." *Interesting Engineering*, https://interestingengineering.com/innovation/us-el-capitan-supercomputer-goes-online. Accessed 25 Sep. 2025.

[5] *November 2024 — TOP500*. https://www.top500.org/lists/top500/2024/11/. Accessed 25 Sep. 2025.

[6] *Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3. Accessed 25 Sep. 2025.

[7] Redell, Bob. "Livermore National Lab's 'El Capitan' Is World's Fastest Supercomputer." *NBC Bay Area*, 29 Nov. 2024, https://www.nbcbayarea.com/news/local/el-capitan-livermore-laboratory-supercomputer/3722644/.

[8] *November 2024 — TOP500*. https://top500.org/lists/green500/2024/11/. Accessed 25 Sep. 2025.

[9] *June 2025 — TOP500*. https://top500.org/lists/green500/2025/06/. Accessed 25 Sep. 2025.

[10] "Slingshot." *Glenn's Digital Garden*, 7 Apr. 2025,
https://glennklockwood.com/garden/Slingshot.

[11] *Purchase HPE Cray Supercomputing Operating System Software*.
https://buy.hpe.com/us/en/software/operating-systems/cray-operating-systems/cray-operating-systems/
hpe-cray-supercomputing-operating-system-software/p/1012842044.

[12] *TOP500 List - June 2025 — TOP500*. https://www.top500.org/lists/top500/list/2025/06/. Accessed 25 Sep. 2025.

[13] *June 2025 HPCG Results*. https://hpcg-benchmark.org/custom/isc25.html. Accessed 26 Sep. 2025.

[14] *June 2025 BFS - Graph 500*. 11 Jun. 2025, https://graph500.org/?page_id=1368.

[15] *Breaking the ICE: ICECap Looks to Use Exascale Fusion Simulations to Pioneer Digital Design — Lawrence Livermore National Laboratory*. https://www.llnl.gov/article/51951/breaking-

ice-icecap-looks-use-exascale-fusion-simulations-pioneer-digital-design. Accessed 26 Sep. 2025.

[16] *LLNL Team Accelerates Multi-Physics Simulations with El Capitan Predecessor Systems — Lawrence Livermore National Laboratory*. https://www.llnl.gov/article/51131/llnl-team-accelerates-multi-physics-simulations-el-capitan-predecessor-systems. Accessed 26 Sep. 2025.

[17] *ICECap Looks to Use Exascale ICF Simulations to Pioneer Digital Design — National Ignition Facility & Photon Science*. https://lasers.llnl.gov/news/icecap-looks-use-exascale-icf-simulations-pioneer-digital-design. Accessed 26 Sep. 2025.