Development of Supercomputers as National Projects

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Abstract

Supercomputer simulations, along with theory and experimentation, have become essential methods in scientific and technological research and are now being employed across a wide range of fields. Recently, the role of supercomputers in AI development has also gained significant importance. Japan has been actively developing supercomputers through national projects, and in March 2021, the supercomputer *"Fugaku"* was launched, achieving world-class computational performance while maintaining high versatility for handling various types of calculations. Currently, discussions are ongoing about the development of *Fugaku's* successor. This article provides an overview of the basic concepts of supercomputers, the history and achievements of Japan's national supercomputer development projects, and explores the trends in supercomputer development in other countries, including the U.S. and China, as well as the technological challenges faced in the next generation of supercomputers.

Introduction

Simulations conducted using supercomputers have become a primary research method in science and technology, alongside theory and experimentation. They hold increasing importance in both academic research and industrial applications. From an economic security perspective, it is crucial for countries to possess high-performance supercomputer technology domestically, and major nations are actively engaged in the development and utilization of such systems.

This article provides an overview of basic information about supercomputers, with a particular focus on Japan's *Fugaku* and K computer. It introduces the development history and operational status of these supercomputers as part of national projects. Additionally, it covers discussions regarding the development of next-generation supercomputers.

I Supercomputers

A supercomputer is defined as a computer with significantly higher performance compared to other computers of its time(1). In this chapter, the basic concepts and information about supercomputers will be explained and described.

1 *Structure*

A supercomputer consists of hardware components such as CPUs for computations, memory for temporarily storing data required for calculations, storage for long-term data retention, and software such as an OS and applications. However, one of the distinguishing features of supercomputers is their network structure, where numerous “compute nodes,” each functioning as an individual computer, are interconnected. This structure allows supercomputers to run multiple programs simultaneously or divide large programs across different compute nodes for parallel execution(2).

In some compute nodes, accelerators such as graphics processing units (GPUs) may be installed alongside CPUs. The use of accelerators offers the advantage of speeding up processes that apply the same type of calculation to large datasets while also reducing power consumption. However, accelerators are less suited for tasks that require handling multiple types of calculations simultaneously or those involving complex conditional branching(3).

In large-scale simulations and other computations that use multiple compute nodes, it is necessary to exchange data between these nodes. This data exchange is handled by a system known as the “interconnect network.” If the interconnect network's performance is insufficient, long waiting times for data exchange can occur after each compute node completes its processing, leading to a slowdown in the execution of the entire program. For a supercomputer to achieve optimal performance, the interconnect network must offer low

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* The most recent access date for the internet information referenced in this paper is February 16, 2024. Additionally, the following units are used to represent large numerical values, such as computational speeds: Mega: 10^6 (1 million), Giga: 10^9 (1 billion), Tera: 10^{12} (1 trillion), Peta: 10^{15} (1 quadrillion), Exa: 10^{18} (100 quintillion)

(1) 岩下武史ほか『スパコンを知る―その基礎から最新の動向まで―』東京大学出版会, 2015, pp.3-4 (IWASHITA Takeshi et al., *Knowing Supercomputers: The Basics and the State-of-the-Art*, University of Tokyo Press, 2015, pp.3-4). Since the computational performance of computers improves year by year, it is not appropriate to set a fixed standard to define a supercomputer as one that exceeds a certain performance level. Rather, it is important to note that supercomputers are defined in comparison to other computers of the same era. Additionally, computational technologies using high-performance computers, including supercomputers, are often referred to as “High Performance Computing (HPC).”

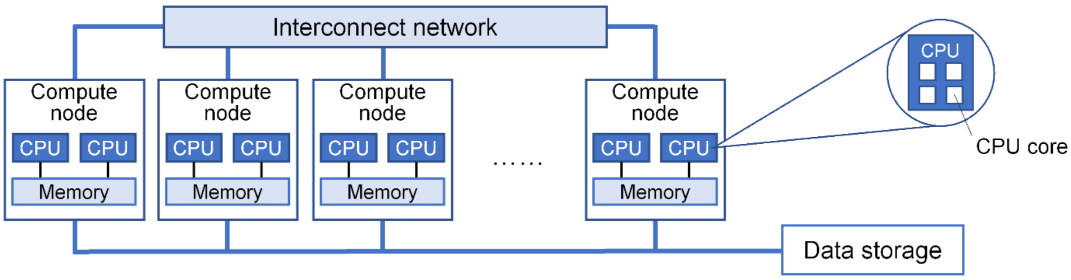
(2) *ibid.*, pp.14-15, 35-42.

(3) *ibid.*, pp.16-17.

latency[(4)] and high throughput[(5)], matching the capabilities of the compute nodes.

Figure 1 illustrates the structure of a supercomputer, which consists of numerous interconnected compute nodes. By performing parallel processing, these compute nodes enable the simultaneous execution of multiple programs and the efficient handling of large-scale computations.

***Figure 1.* Structure of supercomputer**



(Source) Created by the author based on IWASHITA Takeshi et al., *Knowing Supercomputers: The Basics and the State-of-the-Art*, University of Tokyo Press, 2015, pp.14-17.

In addition to the hardware, supercomputers often require specialized software. For instance, supercomputers are typically used collaboratively by many users. In such cases, processing requests, known as "jobs," specify the number of compute nodes required and are assigned by job management software based on the availability of these nodes. This software must ensure fair usage among users, manage waiting times, and optimize the system's overall operational efficiency. Additionally, it must handle job management during execution and address issues such as compute node failures[(6)].

2 *Performance Index*

There are two types of performance indicators for supercomputers: "theoretical peak performance," which represents the maximum possible computational performance, and "effective performance," which is based on actual computation time.

Theoretical peak performance is calculated by multiplying the number of floating-point operations[(7)] per second (FLOPS) that each CPU in the supercomputer can perform by the

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(4) Low latency refers to the short time it takes from when one compute node requests data from another until the first piece of data arrives. High throughput refers to the large amount of data that can be transferred per unit of time. *ibid.*, p.20.
(5) *ibid.*, pp.17-20.
(6) *ibid.*, pp.41-42.
(7) Calculations using double precision floating-point numbers, which represent numbers using 64 bits (64-digit binary). *ibid.*, p.8.

total number of CPUs(8). For example, each compute node of Japan's *Fugaku* supercomputer is equipped with a CPU that has a computational performance of 3.38 teraFLOPS, and the total number of compute nodes is 158,976. Therefore, the theoretical peak performance of *Fugaku* is 537 petaFLOPS(9). Notably, *Fugaku's* computational performance is equivalent to that of approximately 20 million smartphones(10).

Effective performance, on the other hand, is calculated based on the time required to execute performance measurement programs (benchmarks). Since the performance values can vary depending on the benchmarks used, various benchmarks have been developed for different evaluation purposes(11). As discussed in the next section, global rankings of supercomputers are published based on these benchmarks.

3 *World Ranking*

One of the most prominent rankings of supercomputer performance worldwide is the “TOP500,”(12) which is announced twice a year at international high-performance computing (HPC)(13) conferences. The TOP500 ranking is based on the effective performance (LINPACK score) calculated using a benchmark program called “LINPACK,” which solves systems of linear equations(14). As of November 2023, the world's top supercomputer is “Frontier,” developed by the U.S. Department of Energy, with a LINPACK score exceeding 1 exaFLOPS (refer to the figure at the end of the document)(15).

In addition, a ranking called “Green500”(16), which evaluates the performance per watt (power efficiency) of supercomputers listed in the TOP500, is also published. Generally, supercomputers developed for specific applications, such as those equipped with GPUs, are considered to have an advantage in terms of power efficiency compared to those composed solely of CPUs. However, in the Green500 announced in November 2019, the prototype of Japan's *Fugaku*, which consists only of CPUs, achieved the top spot

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(8) *ibid.*, pp.23-25. However, in systems that utilize accelerators, the theoretical peak performance is calculated as the sum of the theoretical peak performances of both the CPU and the accelerator.
(9)「システム紹介」計算科学研究センターウェブサイト (“System Introduction.” RIKEN Center for Computational Science Website)
(10) 松岡聡「スーパーコンピュータ「富岳」の夜明け」2020.7.1, p.6. 文部科学省ウェブサイト (MATSUOKA Satoshi, “The Dawn of the Supercomputer *Fugaku*,” 2020.7.1, p.6. MEXT Website)
(11) 岩下ほか　前掲注(1), pp.7, 25-35 (IWASHITA et al., *op. cit.* (1), pp.7, 25-35).
(12) “TOP500.” TOP500 Website
(13) It is announced yearly in the International Supercomputing Conference (ISC) and Supercomputing Conference (SC), held around June and November, respectively.
(14) 佐藤三久「スーパーコンピュータのベンチマークについて」2020.6.17, p.21. 計算科学研究センターウェブサイト (SATO Mitsuhisa, “Supercomputer Benchmarks,” 2020.6.17, p.21. RIKEN Center for Computational Science Website)
(15) “November 2023.” TOP500 Website
(16) “Green500.” TOP500 Website

globally[17].

Furthermore, rankings based on various benchmarks evaluate practical computational performance. These include "HPCG," which incorporates computational methods used in industrial applications; "Graph500," which assesses processing performance for big data analysis; and "HPL-MxP" (formerly "HPL-AI"), which evaluates processing performance related to artificial intelligence (AI). These benchmarks are referenced according to their respective evaluation purposes[18].

4 *Application Areas*

Supercomputers are utilized in both academic research and industrial research and development. Fields benefiting from supercomputing include drug discovery, new material development, disaster simulations, weather forecasting, and space research[19]. In recent years, supercomputers have also gained importance as computational infrastructure in the development of high-performance AI[20].

For instance, drug discovery typically requires long development periods and substantial costs, and even then, success is not guaranteed. However, supercomputers can help narrow down a vast number of compounds to identify those likely to have beneficial effects on the human body. Moreover, by leveraging supercomputers with high computational performance, it is possible to simulate conditions within the human body and analyze the effects of drugs. These technologies are expected to significantly improve the efficiency of the drug discovery process[21].

Research related to space is another area where the development facilitated by supercomputers is particularly anticipated. In academic research, efforts are being made to validate simulations of the early universe and clarify the processes of star formation within our galaxy using supercomputers[22]. Additionally, in the field of space exploration, supercomputer simulations are used to assess the effects that artificial satellites experience from the space environment, as well as their impact on that environment. Because conducting such research in actual outer space is challenging, analyses performed by

(17) 佐藤　前掲注(14), p.25 (SATO, *op. cit.* (14), p.25).
(18) *ibid.*, pp.26-29.
(19) 岩下ほか　前掲注(1), pp.9-10 (IWASHITA et. al., *op. cit.* (1), pp.9-10).
(20) 小川宏高「人工知能向けスーパコンピュータの技術開発動向」『電子情報通信学会誌』1153 号, 2020.5, p.488 (OGAWA Hirotaka, "Technical Development Trends of Supercomputers for Artificial Intelligence," *The journal of the Institute of Electronics, Information and Communication Engineers*, Vol.103 No.5, May 2020, pp.488-494).
(21) 岩下ほか　前掲注(1), pp.10-12 (IWASHITA et. al., *op. cit.* (1), pp.10-12).
(22) "Supercomputer Turns Back Cosmic Clock." Center for Computational Astrophysics, NAOJ Website; "Sub-project B: From Clouds to Stars and Planets: Toward a Unified Formation Scenario." Joint Institute for Computational Fundamental Science (JICFuS) Website

supercomputers play a crucial role in advancing our understanding of these phenomena[23].

II Chronology of Supercomputer Development in Japan

Since the 1980s, technology related to supercomputers in Japan has advanced significantly, resulting in the global proliferation of supercomputers developed by Japanese companies. However, to address large-scale computational challenges that commercial supercomputers could not handle, the need to develop supercomputers with extremely high performance using domestic technology was recognized, prompting the advancement of supercomputer development as a national project[24].

In 2002, the "Earth Simulator," developed for analyzing and predicting global climate change, achieved approximately five times the computational performance of the U.S. supercomputer "ASCI White," which had previously held the title for the world's highest computational performance, with a LINPACK performance of 35.6 teraFLOPS. This achievement astonished stakeholders in U.S. supercomputing[25].

Since then, Japan has continued its national projects for supercomputer development. This chapter summarizes the development and operation of Japan's K computer and *Fugaku*, along with their accomplishments[26].

1 ***Development and Operation of K Computer***

(1) Development of a "Next-Generation Supercomputer"

The concept for the project to develop a supercomputer, which would later be named the K computer, began in 2005. In August of that year, a meeting of experts convened by the Ministry of Education, Culture, Sports, Science, and Technology (hereinafter referred

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(23) 岩下ほか　前掲注(1), pp.12-14 (IWASHITA et. al., *op. cit.* (1), pp.12-14).

(24) 海洋研究開発機構地球シミュレータ開発史編集チーム編『地球シミュレータ開発史』2010, pp.17-18, 28-29 (Oceanographic Research and Development Organization, Earth Simulator Development History Editorial Team, *Earth Simulator Development History*, 2010, pp.17-18, 28-29).

(25) Referred to as "Computenik" drawing a parallel to the Soviet Union's "Sputnik 1" (launched in 1957), which shocked the United States by becoming the world's first successful satellite. John Markoff, "Japanese Computer Is World's Fastest, As U.S. Falls Back," New York Times, Apr 20, 2002, pp.A1, C14.

(26) In March 2023, the author had the opportunity to visit the RIKEN Center for Computational Science at the Institute of Physical and Chemical Research to conduct on-site research. The author expresses gratitude to those who assisted with the field investigation. Some of the descriptions in the following chapters reflect the information gathered during that visit. However, the responsibility for this paper rests with the author and does not represent the official views of the visited institution.

to as MEXT) proposed the development of a supercomputer capable of exceeding 10 petaFLOPS(27). In response, the "Next-Generation Supercomputer Project" was launched, and in October, the Institute of Physical and Chemical Research (hereinafter referred to as RIKEN), an independent administrative institution, was selected as the main developer of the "Next-Generation Supercomputer"(28). In March 2006, the 3rd Basic Plan for Science and Technology (covering the fiscal years 2006 to 2010) was decided by the Cabinet, positioning the "Next-Generation Supercomputer" as a core technology that should receive concentrated investment during the basic planning period as a national large-scale project(29).

The development of the "Next-Generation Supercomputer" began in the fiscal year 2006, focusing on system configuration discussions and software development(30). In July 2006, the project was designated as a "Specific Advanced Large Research Facility" under the "Act on the Promotion of Public Utilization of the Specific Advanced Large Research Facilities" (Act No. 78 of 1994, hereinafter referred to as the "Public Utilization Promotion Law"). This designation enabled the "Next-Generation Supercomputer" to receive government funding and be made widely available for shared use by researchers from academia, industry, and government (refer to Section 2(6) for the sharing)(31).

The results of the system configuration examination by RIKEN led to the adoption of a scalar-vector hybrid system for the "Next-Generation Supercomputer." This configuration combined the versatility of scalar processors, which are widely used globally, with the strengths of vector processors, particularly in tasks such as weather simulations, where Japan has expertise. The goal was to achieve a LINPACK score of 10 petaFLOPS,

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(27) 科学技術・学術審議会研究計画・評価分科会情報科学技術委員会計算科学技術推進ワーキンググループ「計算科学技術推進ワーキンググループ第 2 次中間報告」2005.8.24, p.46. 文部科学省ウェブサイト（国立国会図書館インターネット資料収集保存事業（WARP）で保存されたページ） (Subdivision on Research Planning and Evaluation, Council for Science and Technology, Working Group on Computational Science Technology Promotion, "Second Interim Report of the Working Group on Computational Science Technology Promotion," August 24, 2005, p.46. MEXT Website (Archived page saved by the National Diet Library's Internet Document Collecting and Preservation Project (WARP)))

(28) 理化学研究所百年史編集委員会企画・編集『理化学研究所百年史　第II編　研究と成果』2018, pp.431-432 (Institute of Physical and Chemical Research, Centenary History Editorial Committee, Planning and Editing, *Centenary History of RIKEN, Volume II: Research and Achievements*, 2018, pp. 431-432). RIKEN has been a National Research and Development Agency since April 2015.

(29) 「科学技術基本計画」（平成 18 年 3 月 28 日閣議決定）pp.14-15. 内閣府ウェブサイト ("Basic Plan for Science and Technology." (Cabinet Decision on March 28, 2006) pp.14-15. Cabinet Office Website)

(30) 理化学研究所百年史編集委員会企画・編集　前掲注(28), pp.432-433 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), pp. 432-433).

(31) 文部科学省「特定放射光施設の共用の促進に関する法律の改正について」『Spring-8 利用者情報』vol.11 no.5, 2006.9 (MEXT, "Regarding the Revision of the Act for the Promotion of Public Utilization of Specific Synchrotron Radiation Facilities," *Spring-8 User Information*, vol. 11, no. 5, September 2006).

with completion targeted for 2012[32].

However, in subsequent meetings of experts convened by MEXT, concerns arose that the expected performance might be insufficient, prompting calls for a re-evaluation of the system configuration. Additionally, the company responsible for developing the vector processor component withdrew from the project, leading to the decision to proceed with the development of a system based solely on scalar processors[33].

(2) Changes to the Plan Following the "Review of Government Programs"

In November 2009, a review of government programs targeted the "Next-Generation Supercomputer Project". During this review, discussions focused on the appropriateness of changing the system configuration from a scalar-vector hybrid to a scalar-only processor-based system, the significance of investing national funds to achieve world-class performance, and the industry's need for 10 petaFLOPS computational capability. Consequently, the project was evaluated as being "a near-cancellation of budget allocation for the next fiscal year.[34]"

On December 9th, the Cabinet Office's Council for Science and Technology Policy (CSTP), now the Council for Science, Technology, and Innovation (hereinafter referred to as CSTI), issued an opinion on the project: "Although the system configuration was changed to a scalar-only system, the 10 petaFLOPS target can be achieved, and the project should be promoted with certainty. However, it is important to ensure that the public fully understands the process and details of this plan change[35]."

Subsequently, on December 16th, 2009, the Minister of Finance, the Minister of State for Government Revitalization, the Minister of State for National Policy, and the MEXT Minister reached an agreement to continue the next-generation supercomputer project with modifications and to include it in the budget proposal. Therefore, the target date for

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(32) 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」文部科学省ウェブサイト（"The innovative High-Performance Computing Infrastructure (HPCI)," Ministry of Education, Culture, Sports, Science and Technology Website); 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.433 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.433) .

(33) 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」同上 (The innovative High-Performance Computing Infrastructure (HPCI), *ibid.*)

(34) 内閣府行政刷新会議事務局「行政刷新会議ワーキングチーム「事業仕分け」第3WG」（3-17）2009.11.13, pp.9,14-16, 18, 21. （国立国会図書館インターネット資料収集保存事業（WARP）で保存されたページ） (Cabinet Office Government Revitalization Unit Office "Government Revitalization Unit Working Team 'review of government programs (jigyou shiwake)' 3rd WG," (3-17) 2009.11.13, pp.9,14-16, 18, 21 (Archived page by the National Diet Library's Internet Resources Collection and Preservation Project (WARP))).

(35) 「「次世代スーパーコンピュータの開発・利用」の平成 22 年度概算要求にかかる見解」2009.12.9. 内閣府ウェブサイト ("Opinion on the FY2010 Budget Request for the 'Development and Utilization of the Next-Generation Supercomputer'," 2009.12.9. Cabinet Office Website)

achieving 10 petaFLOPS performance was postponed from November 2011 to June 2012. Moreover, the focus of the project shifted from a developer-centered approach to a user-centered one, with an emphasis on addressing the diverse needs of users. While still striving for world-class performance, the project aimed to develop the Innovative High-Performance Computing Infrastructure (HPCI), discussed later. This led to the renaming of the "Next-Generation Supercomputer Project" to the HPCI Project, which continued to advance its development(36). In August 2010, MEXT established the HPCI Project Promotion Committee, an expert panel responsible for overseeing the promotion and progress evaluation of the HPCI project(37).

The HPCI is a system that connects the next-generation supercomputer, as its core, with other supercomputers and large-scale storage systems owned by universities and research institutions across Japan via a high-speed network. This infrastructure enables users (researchers from universities, companies, etc.) to access and utilize various supercomputers across the network with a single account, facilitating the sharing of large-scale data between different supercomputers(38).

In July 2010, the name of the next-generation supercomputer was officially designated as the "K computer." The name was chosen because "K" (京 in Japanese) represents the target FLOPS performance of 10 petaFLOPS (10^{16}), which was a key milestone for the supercomputer project(39).

(3) K Computer's Operation and Achievements

Beginning in August 2010, the K computer was manufactured by Fujitsu and delivered to the RIKEN Advanced Institute for Computational Science (now the RIKEN Center for Computational Science) in Kobe. The system was transported from the fall of 2010 until the end of August 2011. By March 2011, part of the system was operational, providing a provisional environment for trial use(40).

In the June 2011 TOP500 rankings, despite being an incomplete system, the K computer achieved a LINPACK score of 8.2 petaFLOPS (theoretical peak performance of

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(36) 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」前掲注(32) ("The innovative High-Performance Computing Infrastructure (HPCI)," *op. cit.* (32))
(37) 文部科学省研究振興局「HPCI 計画推進委員会の設置について」2010.8.10 (Ministry of Education, Culture, Sports, Science and Technology Research Promotion Bureau, "The Establishment of HPCI Project Promotion Committee," 2010.8.10).
(38) 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」前掲注(32) ("The innovative High-Performance Computing Infrastructure (HPCI)," *op. cit.* (32))
(39) 「次世代スーパーコンピュータの愛称は「京（けい）」と決定」2010.7.5. 理化学研究所ウェブサイト ("Name of Next-Generation Supercomputer Decided as "K"," 2010.7.5. Institute of Physical and Chemical Research Website)
(40) 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.437 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.437).

8.8 petaFLOPS), securing the title of the world's fastest supercomputer(41). By November 2011, it surpassed its initial goal, achieving a LINPACK score of 10.5 petaFLOPS (theoretical peak performance of 11.3 petaFLOPS), maintaining the world's number one position for the second consecutive period(42).

On June 29, 2012, the K computer's system was completed, and on September 28, 2012, it commenced operations as a shared facility under the Public Utilization Promotion Law. On the same day, the HPCI system, with the K computer at its core, also began its operation(43).

The total cost of developing the K computer was approximately 111.1 billion yen (7.93 billion yen for system development, 1.26 billion yen for software development, and 1.93 billion yen for facility construction)(44).

***Figure 2.* Supercomputer "K"**

(Source) Provided by RIKEN.

The K computer operated stably for nearly seven years until its decommissioning on August 16, 2019, to make way for its successor, *Fugaku*. During its operational period, the K computer was used by approximately 11,100 users, with around 30% coming from the industrial sector. Remarkable research achievements using the K computer include a heart simulator that replicates the heart's movement at the molecular and cellular level, ultra-high-resolution simulations for typhoon and heavy rain prediction, and systems for predicting complex disasters that were difficult to anticipate using past data. Additionally, the K computer contributed to industrial applications, such as the development of materials for fuel cells. These breakthroughs were made possible by the K computer, as they were computationally impractical with previous supercomputers(45).

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(41) "June 2011." TOP500 Website
(42) "November 2011." TOP500 Website
(43) 理化学研究所百年史編集委員会企画・編集　前掲注(28), pp.437, 442 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), pp.437, 442).
(44) 「「京」の開発資金について」理化学研究所計算科学研究機構ウェブサイト ("The Cost of Development of "K"." RIKEN Advanced Institute for Computational Science Website)
(45) 科学技術・学術審議会研究計画・評価分科会「情報科学技術に関する研究開発課題の事後評価結果①」2021.4, pp.8-9, 11. 文部科学省ウェブサイト (Subdivision on Research Planning and Evaluation, Council for Science and Technology, "Results of Ex-Post Evaluation of R&D Projects Related to Information Science and Technology ①," 2021.4, pp.8-9, 11. MEXT Website)

2 *Development and Operation of Fugaku*

(1) Examination of Post-K computer

The examination for the development of the K computer's successor (hereafter referred to as the Post-K computer) began in 2010. That same year, the research community involved in supercomputing organized a workshop titled Strategic Direction/Development of HPC (SDHPC), which focused on exploring the future of supercomputer development. In July 2011, MEXT established two working groups, the Application Working Group and the Computer Architecture/Compiler/System Software Working Group, to further these discussions(46). From October 2011, these activities were consolidated, and by February 2012, a comprehensive report titled "The Report on the Future HPC Technology Development" (47)was submitted to the HPCI Plan Promotion Committee. This report outlined the technological challenges to be addressed and the necessary development framework for the future of supercomputing(48).
Subsequently, MEXT commissioned the "Feasibility Study on Future HPC Systems" to gather insights into the systems and applications required for the Post-K computer(49).

(2) Development of Post-K Computer

In 2014, the "FLAGSHIP 2020 Project" was launched with the aim of developing the Post-K computer and beginning its operation by 2020(50).

Initially, the plan projected that the Post-K computer would consume between 30 and 40 MW of power (compared to approximately 13 MW(51) for the K computer) and achieve

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(46) 「今後の HPC 技術の研究開発の検討について」（第 5 回 HPCI 計画推進委員会　資料 2）2011.7.14, p.1. 文部科学省ウェブサイト（国立国会図書館インターネット資料収集保存事業（WARP）で保存されたページ） ("The Examination of R&D on Future HPC Technologies," (5th HPCI Program Promotion Committee, Document 2) 2011.7.14, p.1. MEXT Website (Archived by the National Diet Library's Internet Materials Collection and Preservation Project (WARP)))

(47) アプリケーション&コンピュータアーキテクチャ・コンパイラ・システムソフトウェア合同作業部会「今後の HPCI 技術開発に関する報告書」2012.2.10. 文部科学省ウェブサイト (Application & Computer Architecture/Compiler/System Software Working Group, "Report on the Future HPC Technology Development," 2012.2.10. MEXT Website)

(48) 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.456 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.456).

(49) 科学技術・学術審議会研究計画・評価分科会「情報科学技術に関する研究開発課題の中間・事後評価結果」2014.8, pp.13-20. 文部科学省ウェブサイト (Subdivision on Research Planning and Evaluation, Council for Science and Technology, "Interim and Post-Evaluation Results of Research and Development Projects Related to Information Science and Technology," 2014.8, pp.13-20. MEXT Website)

(50) 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.457 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.457).

(51) "November 2011," *op.cit.*(42)

a theoretical peak performance of 1 exaFLOPS. To meet this goal, the system design originally considered using general-purpose CPUs alongside accelerators. However, due to anticipated high costs, the decision was made to proceed with a system composed solely of CPUs, without the inclusion of accelerators(52).

Under the revised system configuration, no specific numerical performance target for computational power was set. Instead, the development objectives shifted to maintaining power consumption between 30 and 40 MW and achieving up to 100 times the performance of the K computer when running real-world applications. As part of the development strategy, the co-design of the system and applications prioritized addressing societal and scientific challenges. Other goals included developing a competitive general-purpose system, fostering strategic international collaboration, maximizing the use of K computer resources (technology, human capital, and applications), and creating a system with the potential for performance expansion beyond its 2020 completion(53).

From October 2014 to the end of August 2015, RIKEN and Fujitsu carried out the basic design for the Post-K computer. The development was divided into two major areas: hardware/system and applications. Thirteen working groups were formed for hardware and system development, and nine working groups were created for application development(54).

In January 2016, the detailed design and prototyping phase for the Post-K computer began(55). At this stage, the initial plan was to use CPUs manufactured with 10 nm microfabrication technology(56). However, due to delays in semiconductor manufacturing technology, achieving the planned performance became difficult. As a result, the development schedule was extended by one to two years. The project transitioned to adopt the next-generation 7 nm microfabrication technology for its CPU, and a new computation method, half-precision floating-point arithmetic, was introduced to enable applications in the AI field(57).

In the summer of 2018, a prototype of the Post-K computer was completed, and performance evaluations were conducted. Based on the results, CSTI approved its

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(52) 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.457 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.457).

(53) *ibid.*, pp.457-458.

(54) フラッグシップ 2020 プロジェクト・理化学研究所計算科学研究センター『富岳コデザイン・レポート―フラッグシップ 2020 プロジェクト・テクニカルレポート―』2022.3, p.23 (FLAGSHIP 2020 Project and RIKEN Center for Computational Science (R-CCS), *Fugaku Codesign Report: FLAGSHIP 2020 Project Technical Report*, March 2022, p.23).

(55) 理化学研究所百年史編集委員会企画・編集　前掲注(28), p.460 (Planned and Edited by RIKEN Centennial History Editorial Committee, *op. cit.* (28), p.460).

(56) n (nano) is 10-9. The higher the precision of microfabrication, the more capable it becomes to manufacture high-performance semiconductor devices.

(57) フラッグシップ 2020 プロジェクト・理化学研究所計算科学研究センター　前掲注(54), p.23 (FLAGSHIP 2020 project and Institute of Physical and Chemical Research RIKEN Center for Computational Science, *op. cit.* (54), p.23).

production, which commenced in January 2019[58].

In May 2019, through a public contest, the name “*Fugaku*” (富岳) was chosen for the Post-K computer. The name “*Fugaku*” refers to Mount Fuji, symbolizing the computer's high performance, with the mountain's broad base representing the wide range of users who will benefit from its capabilities[59].

(3) *Fugaku's* Operation Start and Performance Evaluation

From December 2019 to May 2020, the system units of *Fugaku* were transported and installed at the RIKEN Center for Computational Science (R-CCS), located on the site of the former K computer. On March 9, 2021, the entire *Fugaku* system was completed, and it began operation as a shared facility under the Public Utilization Promotion Law[60]. The national cost for *Fugaku's* development, including application development, is estimated at approximately 110 billion yen[61]. Additionally, since *Fugaku's* shared use began, an annual budget of approximately 15 billion yen has been allocated for its operational expenses[62].

Before *Fugaku* was fully operational, in June 2020, global rankings from various benchmark tests were released, revealing that *Fugaku* had achieved the top position in the TOP500 list with a LINPACK score of 416 petaFLOPS (theoretical peak performance of 514 petaFLOPS). This marked the first time in 8.5 years that a Japanese supercomputer had held this title since the K computer. *Fugaku's* performance extended beyond the TOP500, securing first place in other prestigious rankings, including HPCG, Graph500, and HPL-AI (refer to I 3), demonstrating its versatility across a wide range of

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(58) 同上, pp.23-24 (*ibid.*, pp.23-24); 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」 前掲注(32) (“The innovative High-Performance Computing Infrastructure (HPCI),” *op. cit.* (32))

(59) 「ポスト「京」の名称 「富岳（ふがく）」に決定」2019.5.23. 理化学研究所ウェブサイト (“Name of Post-K Computer Decided as “*Fugaku*”,” 2019.5.23. RIKEN Website)

(60) With the termination of the K computer's operation and the commencement of *Fugaku*'s operation, the Ordinance for Enforcement of the Act on the Promotion of Public Utilization of the Specific Advanced Large Research Facilities was amended. As a result, *Fugaku* was newly designated as a “Specific Advanced Large Research Facility” under the Public Utilization Promotion Law (Order No. 16 of 2019, Ministry of Education, Culture, Sports, Science and Technology); 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」 前掲注(32) (“The innovative High-Performance Computing Infrastructure (HPCI),” *op. cit.* (32)); 「スーパーコンピュータ「富岳」完成、共用開始」2021.3.9. 理化学研究所ウェブサイト (“Supercomputer ‘*Fugaku*’has been completed and has started shared use,” 2021.3.9. RIKEN Website)

(61) 「開発資金について」計算科学研究センターウェブサイト (“About the Cost of Development.” RIKEN Center for Computational Science Website)

(62) 「世界最高水準の大型研究施設の整備・利活用」2023.1. 文部科学省ウェブサイト (“Establishment and Utilization of World-Class Large Research Facilities,” 2023.1. MEXT Website); 「世界最高水準の大型研究施設の整備・利活用」2022.1. 同 (“Establishment and Utilization of World-Class Large Research Facilities,” 2022.1, *ibid.*)

computational tasks. *Fugaku* maintained its leadership for two years (four consecutive periods) until the U.S. supercomputer "Frontier" claimed the top positions in the TOP500 and HPL-MxP rankings in June 2022. As of November 2023, *Fugaku* continues to hold the #1 position in both HPCG and Graph500, achieving this distinction for four years (eight consecutive periods)(63).

To implement the co-design of systems and applications, nine target applications(64) were selected as part of *Fugaku's* development policy. Performance evaluations conducted on the completed *Fugaku* revealed an enhancement in performance compared to the K computer, achieving at least a 23-fold increase and a maximum improvement of 131 times. Additionally, the maximum power consumption was kept to 30 MW. Consequently, the development objectives for *Fugaku* were met(65).

Figure 3. **Supercomputer *Fugaku***

(Source) Provided by RIKEN.

(4) *Fugaku's* Achievements

In early 2020, as the deployment of *Fugaku* was underway, the global spread of COVID-19 occurred. In response, RIKEN allocated a portion of *Fugaku's* computational resources, which were being prepared for shared use starting in fiscal year 2021, to research and development aimed at addressing COVID-19. One example of research conducted under this initiative was the droplet and aerosol dispersion simulation related to the novel coronavirus. This simulation assessed infection risk under various conditions, and the results were utilized to aid in policy formulation and the establishment of guidelines for

(63) "Supercomputer *Fugaku*." TOP500 Website; "RESULTS." HPL-MxPWebsite; 「スーパーコンピュータ「富岳」の世界ランキング結果について」2023.11.14. 富士通株式会社ウェブサイト (“Supercomputer *Fugaku*'s World Ranking Results,” 2023.11.14. Fujitsu Website) Since November 2020, *Fugaku* has been conducting benchmarks utilizing all of its designed computational resources. In the TOP500 list, it achieved a LINPACK performance of 442 petaFLOPS, with a theoretical peak computational performance of 537 petaFLOPS.

(64) GENESIS (Calculation of protein dynamics), Genomon (genome analysis), GAMERA (Calculation of earthquakes in crustal and urban settings), NICAM+LETKF (Simulation of the Earth's atmosphere by integrating observational data), NTChem (Elucidation of molecular structures), ADVENTURE (Simulation of large-scale systems), RSDFT (Investigation of material properties), FrontFlow/blue (Calculation of turbulent flows and acoustics), and LQCD (Calculation of particle behavior). 「スーパーコンピュータ「富岳」の開発」2019.11. 計算科学研究センターウェブサイト (“The Development of Supercomputer *Fugaku*,” 2019.11. RIKEN Center for Computational Science Website)

(65) フラッグシップ 2020 プロジェクト・理化学研究所計算科学研究センター 前掲注(54), p.36 (FLAGSHIP 2020 project and Institute of Physical and Chemical Research RIKEN Center for Computational Science, *op. cit.* (54), p.36).

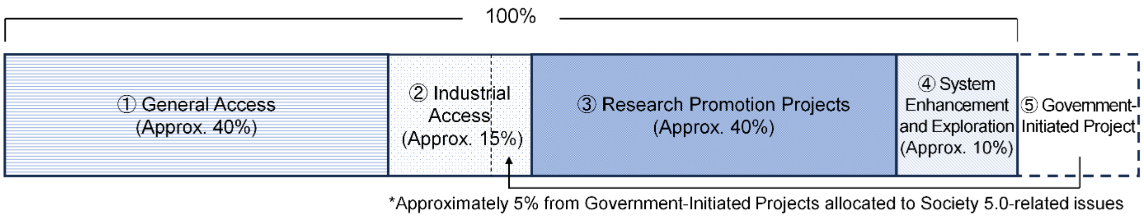
infection control(66).

Since its commencement of shared use, *Fugaku* has been utilized for simulations across various fields, including meteorology, materials science, space, and medicine, with numerous achievements reported. Research involving the development of AI models using *Fugaku*, as well as studies that integrate simulations conducted on *Fugaku* with AI methodologies, have also been undertaken(67).

(5) *Fugaku's* Computational Resources Allocation

The computational resources of *Fugaku* are allocated into five categories based on the Basic Policy established by the MEXT. These resources are shared in accordance with the framework of each designated category (Figure 4).

***Figure 4. Fugaku's* Computational Resources Allocation**



(Source) Created by the author based on 文部科学省「スーパーコンピュータ「富岳」利活用促進の基本方針」2020.7.17, p.3 (MEXT "Basic Policy for Promoting the Use of Supercomputer *Fugaku*," 2020.7.17, p.3).

The "① General Access Category" is primarily intended for the academic community, accounting for approximately 40% of the resources. This category encompasses a wide range of research topics, which are evaluated and selected based on scientific criteria. The "② Industrial Access Category" is designed for use by the industrial sector and represents approximately 15% of the resources. This category covers a broad range of research topics, with evaluations and selections made based on both scientific and socio-economic perspectives. Additionally, within the Industrial Access Category, approximately 5% of computational resources are allocated to research projects related to the promotion of

(66) 「新型コロナウイルス対策を目的としたスーパーコンピュータ「富岳」の優先的な試行的利用について」2020.4.7.理化学研究所ウェブサイト ("The Priority Trial Use of the Supercomputer *Fugaku* for COVID-19 Measures," 2020.4.7. Institute of Physical and Chemical Research Website) This research received the 2021 Gordon Bell Special Prize for High Performance Computing-Based COVID-19 Research, which recognizes the most notable achievements in scientific and technological research utilizing supercomputers (specifically, the research conducted by RIKEN and Kobe University, titled "Droplet and Aerosol Dispersion Simulation of COVID-19 Using *Fugaku*," was awarded the Gordon Bell Prize for COVID-19 research" 2021.11.19. *ibid.*)

(67) 「「富岳」ユーザーの主な研究成果」計算科学研究センターウェブサイト ("*Fugaku* Users' Main Research Achievements." RIKEN Center for Computational Science Website)

Society 5.0(68), sourced from the Government-Initiated Projects framework (which falls outside the 100% allocation). The "③ Research Promotion Projects" category is intended for research topics expected to yield results that directly address scientific and societal issues in a timely manner, accounting for approximately 40% of the resources. The "④ System Enhancement and Exploration Category" supports the stable operation of *Fugaku*, involving system adjustments, research, and development related to user support and the expansion of usage, primarily conducted by RIKEN, representing approximately 10% of the resources. Lastly, the "⑤ Government-Initiated Projects" category addresses issues deemed to be of policy significance or urgency and is allocated resources outside the main computational resources framework(69).

Note that the usage fees for *Fugaku* are waived if the research results are made publicly available. However, there is also a paid option available that allows users to prioritize job execution or to keep results confidential(70).

(6) *Fugaku's* Shared Use Arrangement

Under the Shared Use Promotion Act, the development, maintenance, and sharing of *Fugaku* is conducted by RIKEN, which is the facility's operator (Article 5). Additionally, the MEXT Minister can delegate usage promotion services, such as user selection and usage support, to registered institution promoting use of facilities (Article 8). The Research Organization for Information Science and Technology (RIST) has been designated as the sole registered institution for the use of *Fugaku*(71). Figure 5 illustrates the framework for the shared use of *Fugaku*.

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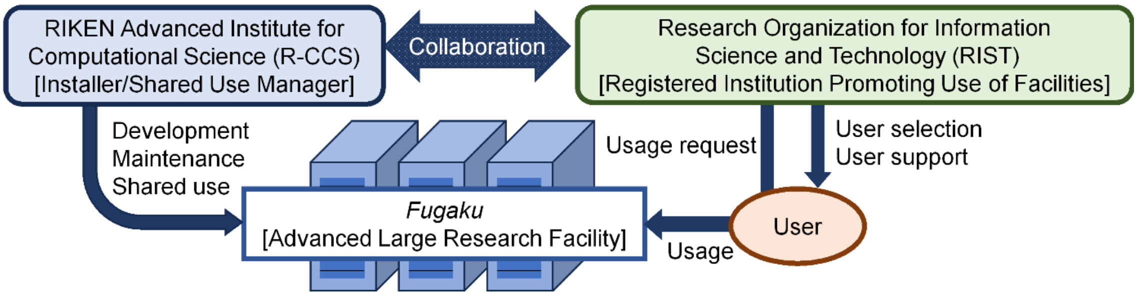
(68) A human-centered society in which economic development and the resolution of social issues are compatible with each other through a highly integrated system of cyberspace and physical space. 「Society 5.0」内閣府ウェブサイト（"Society 5.0," Cabinet Office Website)

(69) 文部科学省「スーパーコンピュータ「富岳」利活用促進の基本方針」2020.7.17 (MEXT, "Basic Policy for Promoting the Use of Supercomputer *Fugaku*," 2020.7.17).

(70) 同上, pp.3-4 (*ibid.*, pp.3-4); 「有償利用の特徴」HPCI ウェブサイト（"Features of Paid Use," HPCI Website).

(71) 「登録施設利用促進機関について」文部科学省ウェブサイト（"Registered Facility Utilization Promotion Agencies." MEXT Website)

Figure 5*. Framework of Shared Use of *Fugaku



(Source) Created by the author based on「1「富岳」の共用と組織　1-1 共用の枠組み」『富岳年報 2022』計算科学研究センターウェブサイト (“1 - Shared Use and Structure of *Fugaku* - 1-1 Framework of Shared Use,” *Fugaku Annual Report 2022*, RIKEN Center for Computational Science (R-CCS) Website).

The Research Organization for Information Science and Technology (RIST) operates a help desk as part of its efforts to provide usage support. Users can access information and technical assistance related to the utilization of *Fugaku* through this centralized help desk. The *Fugaku* operator, the R-CCS, regularly shares operational information and technical expertise with RIST to collaborate on the management of the help desk(72).

(7) Initiatives to Expand the Use of *Fugaku*

To expand the user base of *Fugaku*, the R-CCS is implementing two approaches: “Cloudification of *Fugaku*” and “*Fugaku*-ization of Cloud.”

The “Cloudification of *Fugaku*” approach involves cloud service providers acting as intermediaries between users and *Fugaku*, enabling the supercomputer to be utilized as a cloud service. This aims to create an environment where users without specialized knowledge of supercomputers can easily access *Fugaku's* computational resources through applications and support provided by the service providers(73). Trial initiatives were conducted between 2020 and 2021, confirming the existence of demand for such a system. However, challenges related to procedural complexities, such as submitting project proposals and user reports, as well as limitations on usage purposes due to existing regulations, were also identified(74).

The “*Fugaku*-ization of the Cloud” approach aims to establish an environment where

(72) 「4「富岳」の利用支援　4-1 利用支援」『富岳年報　2022』計算科学研究センターウェブサイト (“4 - *Fugaku* Usage Support, 4-1 Usage Support,” *Fugaku Annual Report 2022*. RIKEN Center for Computational Science (R-CCS) Website) The collaboration between R-CCS and RIST is based on the interviews mentioned above (26).
(73) 「富岳クラウドプラットフォーム」計算科学研究センターウェブサイト (“*Fugaku* Cloud Platform.” R-CCS Website)
(74) 松岡聡「富岳クラウド的利用—試行的実施の成果と課題—」2022.3.16, pp.[7, 9]. 文部科学省ウェブサイト (MATSUOKA, Satoshi, “Cloud-based Use of *Fugaku* - Results and Challenges from Trial Implementation,” 2022.3.16, pp. [7, 9]). MEXT Website)

software developed from the *Fugaku* project can be directly utilized on the cloud, allowing a broad range of users, including potential users of *Fugaku*, to benefit from its achievements. R-CCS refers to this concept as "Virtual *Fugaku*" and has signed a memorandum of understanding with major cloud service provider Amazon Web Services (AWS) to implement *Fugaku* applications in AWS's cloud environment(75).

III Development Towards the Next-Generation Computer

1 *Consideration for Post-Fugaku Development*

In preparation for the development of *Fugaku's* successor (hereafter referred to as "Post-*Fugaku*"), the "Next-Generation Computing Infrastructure Review Subcommittee" was established under the Information Committee of the Council for Science and Technology at MEXT. Discussions began in November 2020(76). By August 2021, an interim summary was compiled, concluding that "strategic national development of next-generation computing infrastructure for the Post-*Fugaku* era is essential, " and a direction for realizing this was outlined(77).

Since the fiscal year 2022, MEXT has been conducting commissioned "Feasibility Studies on Next-Generation Supercomputing Infrastructures" to examine system configuration and identify necessary technological components for Post-*Fugaku*(78).

2 *Development Trends of exaFLOPS-Class Supercomputers in Major Countries*

The development of exaFLOPS-class supercomputers is progressing in the US, China, and Europe.

In the U.S., the Department of Energy is developing three exaFLOPS-class supercomputers: "Frontier, " "Aurora, " and "El Capitan. " Of these, "Frontier" was

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(75) 「バーチャル富岳」計算科学研究センターウェブサイト ("Virtual *Fugaku*." R-CCS Website)
(76) 「革新的ハイパフォーマンス・コンピューティング・インフラ（HPCI）について」前掲注(32) ("The innovative High-Performance Computing Infrastructure (HPCI)," *op.cit.* (32))
(77) 科学技術・学術審議会情報委員会次世代計算基盤検討部会「次世代計算基盤検討部会中間取りまとめ」2021.8.27, pp.15-22 (Council for Science and Technology, Information Committee, Next-Generation Computing Infrastructure Review Subcommittee, "Interim Summary of the Next-Generation Computing Infrastructure Review Subcommittee," 2021.8.27, pp.15-22).
(78) 文部科学省「令和４年度「次世代計算基盤に係る調査研究」公募要領」2022.5. (MEXT, "FY 2022 'Feasibility Studies on Next-Generation Supercomputing Infrastructures' Application Guidelines," 2022.5)

completed in May 2022, achieving over 1 exaFLOPS with a LINPACK score of 1.1 exaFLOPS for the first time in the world, making it the world's top supercomputer on the TOP500 list in June 2022. “Aurora” was completed in June 2023 and ranked second on the November 2023 TOP500, following “Frontier. ” "El Capitan” is scheduled to be completed in 2024.(79)

In China, two exaFLOPS-class supercomputers are under development: the “Tianhe-3”, the successor to “Tianhe-2”, which held the top position in the TOP500 for six consecutive periods starting in June 2013, and the “Sunway OceanLight”, the successor to “Sunway TaihuLight”, which became the first supercomputer to reach the top of the TOP500 list in June 2016 using Chinese-made CPUs. However, as of November 2023, neither of these two machines is listed on the TOP500, and their exact performance remains undisclosed(80).

In Europe, the “EuroHPC JU” project was launched in 2018, with participation from the EU and member states, aiming to elevate Europe's supercomputing technology to the top global level. Under this project, eight supercomputers, including three with several hundred petaFLOPS, have been developed thus far(81). Currently, plans are underway to develop two exaFLOPS-class supercomputers. One will be installed at the Jülich Supercomputing Centre (JSC) in Germany, and the other at the Grand Equipement National de Calcul Intensif (GENCI) in France(82).

3 *Performance Limitations of Supercomputers and the Potential of New Computational Principles*

There is an industry rule of thumb known as “Moore's Law,” which states that “the density of transistors on an integrated circuit doubles every 18 months at a constant cost.” Computers, including supercomputers, have improved their performance by incorporating processors with a large number of transistors in line with this principle. However, recent reports suggest that due to the limits of microfabrication technology, it is becoming increasingly difficult to achieve performance improvements in the same manner as

(79) “Frontier supercomputer debuts as world’s fastest, breaking exascale barrier,” May 30, 2022. Oak Ridge NationalLaboratory Website; “Aurora Supercomputer Blade Installation Complete,” June 22, 2023. Intel Website; “Road to El Capitan 1: It takes a village,” August 14, 2023. Lawrence Livermore National Laboratory Website; “November 2023,” *op.cit.* (15)

(80) Depei Qian and Zhongzhi Luan, “High Performance Computing Development in China: A Brief Review and Perspectives,”Computing in Science & Engineering, vol.21 no.1, 2019.1・2, p.8; 「エクサスケール・コンピューティングへの中国の静かな旅」2023.10.2. HPCwire Japan ウェブサイト (“China’s Silent Trip to Exascale Computing,” 2023.10.2. HPCwire Japan Website).

(81) “Our supercomputers.” EuroHPC JU Website

(82) “Jupiter Technical Overview: A Deep Dive Into Jupiter’s Building Blocks.” Jülich Supercomputing Centre Website; “The Jules Verne Consortium Will Host the New EuroHPC Exascale Supercomputer in France,” 20 June 2023. EuroHPC JU Website

before[(83)].

Another limitation stems from power consumption. Current supercomputers achieve high computational performance by connecting a large number of processors, but the more processors are used, the greater the power consumption. Although the power efficiency of supercomputers improves year by year[(84)], there are constraints on overall power consumption, making it difficult to significantly increase the number of processors[(85)].

Continuous improvements in computational performance through the extension of conventional technologies are becoming less feasible. Conversely, in recent years, research on computers operating on principles different from conventional ones, such as quantum computers, has been advancing. In the research and studies aimed at the development of Post-*Fugaku*, the possibility of integrating these new computational principles with supercomputers is also being considered[(86)].

Conclusion

In national supercomputer development projects, it is crucial not only to incorporate cutting-edge technologies to achieve high performance but also to establish mechanisms that ensure these supercomputers are effectively utilized across a wide range of fields.

In this regard, R-CCS is working to expand the use of *Fugaku*; however, institutional challenges remain. For example, the Public Utilization Promotion Law mandates that the usage of shared facilities such as *Fugaku* must include elements of testing, research, and development related to science and technology (Article 1). Consequently, companies are restricted from using *Fugaku* for purely commercial purposes that do not include these elements. Furthermore, companies may hesitate to use *Fugaku* because it can be difficult to determine whether their intended usage qualifies as testing, research, or development under the law. These restrictions are viewed as barriers to the industrial use of *Fugaku*[(87)].

Supercomputer development has now entered a new phase, and how Japan addresses the emerging limits of conventional technologies and incorporates new ones will impact the country's competitiveness in science, technology, and industry. There is increasing anticipation for the creation of more effective frameworks that can accommodate the

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(83) INOUE Keisuke, "A Study of the Evolution of "Moore's law"," *The Journal of Science Policy and Research Management*, Vol.35 No.2, 2020.8, pp.263-276.

(84) For example, in the transition from the K computer (LINPACK performance of 10.5 petaFLOPS and power consumption of 12.7 megawatts) to *Fugaku* (LINPACK performance of 442 petaFLOPS and power consumption of 29.9 megawatts), the computational performance increased by approximately 42 times, while the increase in power consumption was kept to approximately 2.4 times.

(85) 佐藤　前掲注(14), p.24 (SATO, *op. cit.* (14), p.24).

(86) 文部科学省　前掲注(78), p.14 (MEXT, *op. cit.* (78), p.14).

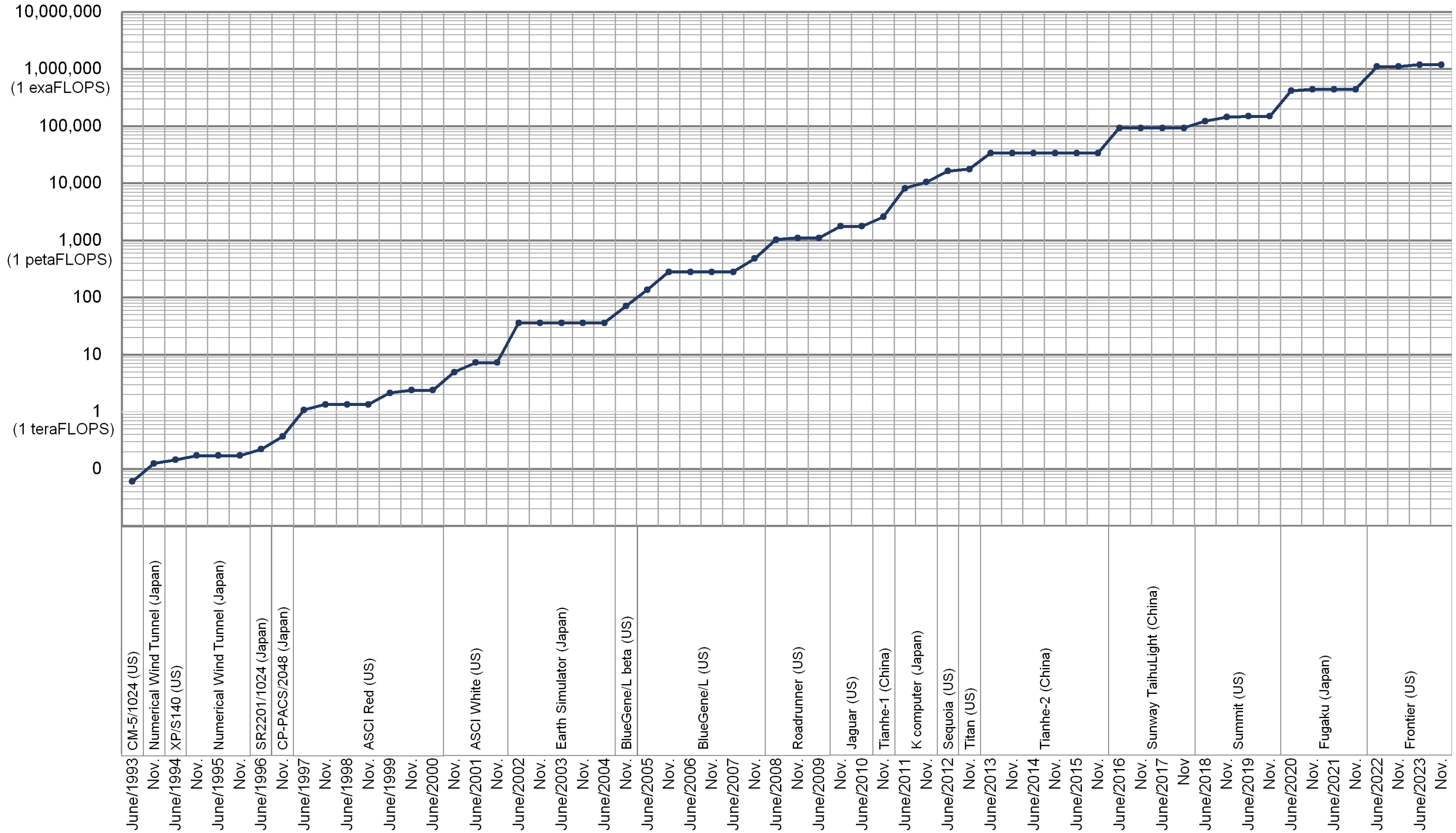
(87) According to a previously cited interview (26).

expanding range of fields and meet the growing demand for supercomputer use.

NAKAMURA Shinya, *Development of Supercomputers as National Projects* (Research Materials), 2025e-2, Tokyo: Research and Legislative Reference Bureau, National Diet Library, 2025.

ISBN: 978-4-87582-942-3

Appendix Chart: Transition of LINPACK Performance of Supercomputers Ranked First in the TOP500 (Unit: teraFLOPS)



(Source) Created by the author based on "TOP500." TOP500 Website