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Review Article

An Overview of Computer Memory Systems and Emerging Trends

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Abstract: Central processing units (CPUs) in modern computing devices rely on computer memory systems to store and retrieve the data they require to perform their duties. This research covers the types, functions, and historical evolution of computer memory systems. It also looks at new developments in memory technology that are influencing the direction of computing. Using the search criteria "computer memory system" AND (PUBYEAR > 2019-2023), a thorough review of all publications published between 2019 and 2023 was conducted in the Web of Science database and IEEE Xplore database. The results were reported in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) standards. In the instance of Web of Science, the database searches yielded a total of 28, 423 results, and 98,142 results in the case of IEEE Xplore. After reading the papers' abstracts, 126,263 search results were eliminated since they didn't fit the criteria. The remaining 302 articles were considered. A total of 32 studies were chosen for inclusion in the review after applying inclusion and exclusion criteria. The thorough analysis outlines the current state of computer memory systems as well as any new trends. Additionally, the report outlines prospective research goals and avenues for computer memory systems research.

Keywords: Non-Volatile Memory (NVM), Quantum Memory, Neuromorphic Memory, Computer Memory System, Memory Hierarchy, 3D XPoint, Resistive RAM (ReRAM), Persistent Memory (PMEM)

1. Introduction

Any physical component that can store data either momentarily or permanently is considered computer memory. The most important component of a computer is its memory.

1.1. Types of Computer Memory

1) Primary or Main Memory
   a. Random Access Memory (RAM)
   b. Read Only Memory (RAM)
2) Cache Memory
   a. Level 1 (L1) cache
   b. Level 2 (L2) cache
3) Secondary Memory
   a. Optical Media Devices
   b. Magnetic Media Devices

1.2. Primary Memory

To begin with, an important characteristic of primary memory is its short access time. Random Access Memory (RAM) is a type of primary that can offer almost rapid access to data, unlike secondary storage devices like hard drives or solid-state drives (SSDs). Because RAM is created using semiconductor technology and is linked to the computer's processor directly through a memory controller, this is the case. RAM's high access speed allows the CPU to retrieve and process data much more quickly, which improves system responsiveness and reduces latency [4].

One of the core advantages of main memory is quick access times. In contrast to secondary storage devices like hard drives or solid-state drives (SSDs), RAM offers almost instantaneous data access. This is because RAM is produced using semiconductor technology and is linked to the computer's processor via a memory controller. System responsiveness and latency are increased thanks to the processor's ability to retrieve and handle data at a considerably faster pace thanks to RAM's quick access speed [1]. Primary memory is also very important for managing virtual memory [17].

1.3. Read Only Memory (ROM)

A group of storage components used in computers and other electronics. It is non-volatile and the data saved there cannot be altered. The main processor's basic bootstrapping firmware, as well as the numerous firmware required to internally control self-contained devices like graphics cards, hard drives, DVD drives, etc., are all stored in ROM.

1.4. Cache Memory

The compact, quick form of memory known as cache, or CPU cache, is placed nearer to the central processing unit (CPU) than the main memory (RAM). Its function is to shorten the average access time of the CPU by temporarily storing frequently accessed data and instructions.

The locality principle, which governs how cache memory works, argues that programs prefer to access data and instructions that are close to one another in memory. It has several levels, commonly referred to as L1, L2, and L3 cache, each of which is larger but slower than the one before it.

1.5. Secondary Memory (Storage)

Data storage and retrieval depend on storage, also known as secondary memory, which is a fundamental component of computer science. It is an essential part of any computing system since it provides a non-volatile and long-term storage solution. In contrast to primary memory (RAM), which is volatile and loses data when the power is interrupted, secondary memory keeps data even when the computer is turned off. This characteristic makes it ideal for the long-term archival of substantial amounts of frequently accessible data. Secondary memory can be categorized into two main types:

1) Magnetic
2) Solid-state

Data is stored and retrieved using magnetism in magnetic storage devices including hard disk drives (HDDs) and magnetic tape [11]. Data is read from and written using read/write heads on one or more rotating platters covered in a magnetic substance in HDDs. They have a large storage capacity and are frequently found in personal computers, servers, and data centers. Their average capacities range from several hundred gigabytes to many terabytes.

On the other hand, magnetic tape is a sequential storage media that utilizes a substantial length of plastic tape that has been magnetically coated. Due to its somewhat sluggish access speed, it is mostly used for archiving purposes, but it provides significant store capacity at a lesser price than HDDs.

Flash memory technology is used by solid-state storage devices to store and retrieve data, including solid-state drives (SSDs) and USB flash drives [12]. Solid-state storage contains no moving elements, in contrast to magnetic storage, which relies on spinning disks or tapes. This leads to quicker access times, less power usage, and increased durability.

1.6. Virtual Memory

Operating systems employ virtual memory as a method to increase the amount of memory that is accessible above and beyond the physical RAM limits of the computer. Programs can operate as though they had access to more memory than is actually available. Virtual memory is made up of a piece of the computer's secondary storage, typically a hard disk, as well as physical memory (RAM).

The operating system divides virtual memory into pages, which are predetermined-size blocks. When RAM becomes full, these pages can be swapped out with ones from secondary storage. These pages are loaded into RAM as needed. Programs can execute despite having little physical memory because to this switching process called paging.

1.7. Tertiary Memory

Tertiary storage, commonly referred to as secondary computer memory, is a category of storage medium intended for long-term data preservation and sparse access. It serves as an extended storage solution beyond primary and secondary memory, offering a trustworthy and cost-effective option for archiving and backup purposes. Tertiary memory differs from primary memory (RAM) and secondary memory (hard disk drives, solid-state drives) in that it is non-volatile, meaning that data is maintained even if power is interrupted. It is therefore suitable for storing information that needs to be kept secure for a long time, such as historical records, legal papers, and research data.

Tertiary memory uses a variety of strategies to fulfill its goals. Among the most popular technologies is optical storage, which includes Blu-ray discs, digital versatile discs (DVDs), and compact discs (CDs). In order to store data on these discs, laser beams are used to etch holes into the disc's surface. These holes are then read by a laser beam to retrieve the data. For long-term archive uses, optical storage is ideal due to its high capacity and durability.

The use of archival disks, also known as write-once, read-many (WORM) disks, is another feature of some tertiary memory solutions [2]. These disks are designed to only allow for a single write before switching to read-only mode. This makes the stored data valid for compliance and regulatory requirements and guarantees its integrity and immutability.

1.8. Functions of Computer Memory

A computer system's ability to function depends heavily on its memory. It acts as the main repository for the information and instructions required to run programs. Data storage, data retrieval, data processing, temporary storage, and multitasking support are all purposes of computer memory. Memory makes processing and task execution more effective by storing and retrieving data quickly. Performance is optimized by bringing frequently used information closer to the CPU thanks to memory arrangement in a hierarchy [3]. In the 1930s, rotating cylinders with magnetic coatings were utilized in magnetic drums to retain data. These procedures were laborious, slow, and had little room for storage [9]. In general, computer memory is a crucial part that facilitates a computer system's efficient operation and performance.

1.9. Data Storage

The act of keeping and storing data on a storage medium is referred to as data storage. It entails the use of tools and platforms to store data in a variety of structured formats, including files, databases, and other formats. Different kinds of storage devices, such as hard disk drives (HDDs), solid-state drives (SSDs), optical storage, magnetic tapes, and cloud-based storage options, can be used to store data. In Data retrieval, accessing and obtaining stored data from a storage medium is known as data retrieval. Based on user requests or software specifications, it entails looking for and accessing particular data. Depending on the storage media and access mode, the retrieval procedure may be sequential or random. For retrieving, evaluating, and altering stored data, data retrieval is crucial. In Data Processing, executing operations or transformations on the obtained or stored data constitutes data processing. To glean insightful information or produce significant results, these processes may involve calculating, sorting, filtering, aggregation, or other manipulations. A physical component like the CPU or specialized software programs built for particular data processing tasks can process data.

1.10. Memory Hierarchy

Memory hierarchy describes how various forms of memory are arranged and ranked in a computer system as shown in figure 1. It has different memory tiers, each with a distinct capacity, access speed, and price. Registers, cache memory, random-access memory (RAM), and secondary storage components like hard drives or SSDs often make up the memory hierarchy.

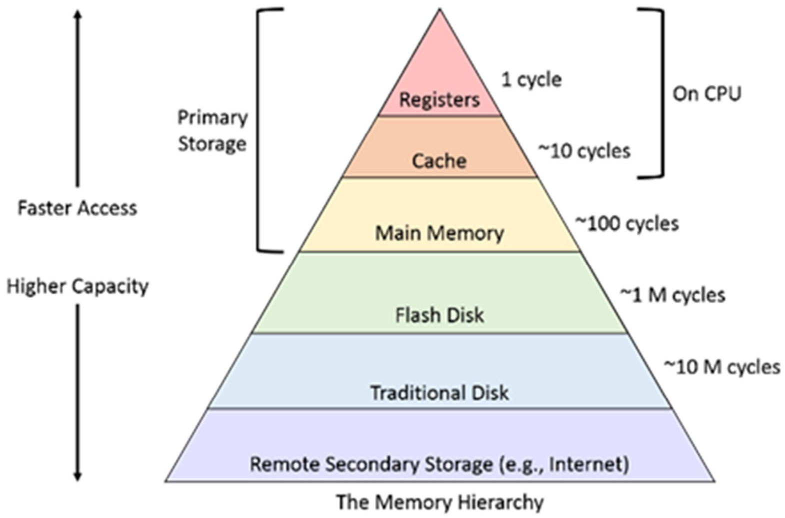

Figure 1. *Computer Memory Hierarchy.*

2. Methodology

2.1. Purpose and Scope

This study focuses on generating a comprehensive literature review to evaluate computer memory systems and emerging trends. To this end, the overview seeks to answer the question on computer memory hierarchy with specific reference to:

1) cost
2) speed
3) size
4) Hardware and functionality

2.2. Systematic Review

A comprehensive review was carried out using the PRISMA protocol [6] to report on the search results [5]. Further Bibliographic analysis was conducted using the VOS viewer software and R Studio to construct networks of scientific publications, researchers, and keyword items in these networks as connected by co-authorship, co-citation, bibliographic coupling and co-citation links as captured in Table 1.

2.3. Search Strategy

The researchers conducted literature search and initial screening thus, the abstracts of highly cited papers were screened independently, while full article screening and data extraction was conducted to obtain articles that were fit for purpose.

The selection criteria included all studies examining computer memory. 2019-2023 was the publication range. Only English text publications were included. The last time the search was updated was August 29, 2023. Figure 3 shows the PRISMA Flow chart used to filter database searches on titles and abstracts to find possibly pertinent records for full-text screening. To find records for full-text screening, the titles and abstracts of all remaining records were scrutinized for eligibility. To find records to include in the evaluation, all records designated for full-text screening were reviewed. Then, from the studies chosen for final inclusion, any information that would be pertinent to the review was retrieved and compiled in a spreadsheet as follows: information about the publication, the specific Author, and the number of citations. Because the articles included in this study were so diverse, a meta-analysis was not done. Therefore, a descriptive approach to data synthesis was adopted, whereby summaries of included studies were presented.

Table 1. *Search Results from Web of science and IEEE Xplore databases.*

Description	Results
Timespan	2019:2023
Sources (Journals, Books, etc)	160
Documents	302
Average years from publication	2.14
Average citations per documents	158.3
Average citations per year per doc	44.02
References	2
DOCUMENT TYPES	
article	250
article; proceedings paper	1
review	50
review; book chapter	1
DOCUMENT CONTENTS	
Keywords Plus (ID)	10
Author's Keywords (DE)	6
AUTHORS	
Authors	1676
Author Appearances	1855
Authors of single-authored documents	4
Authors of multi-authored documents	1672
AUTHORS COLLABORATION	
Single-authored documents	4
Documents per Author	0.18
Authors per Document	5.55
Co-Authors per Documents	6.14
Collaboration Index	5.61

2.4. Limitations

The main limitations of this comprehensive review are the following two points:

1) Language bias. Only English was included in the search strategy. But more languages could have been included in the search process to eliminate linguistic prejudice.
2) Abstracts covered. Due to the difficulty in determining whether a study met all the inclusion requirements, this thorough evaluation did not include any articles or studies that just offered abstracts. As a result of this review's inability to cover all the articles, particularly those with gray regions, this fact, however, became one of its shortcomings.

2.5. Results and Bibliometric Analysis

According to the PRISMA Flow chart in Figure 3, a total of 126,565 articles were produced by electronic searches. 302 studies were left after duplicates were eliminated and studies that didn't fit the criteria were disregarded after studying the abstract. 35 studies were chosen for the review after the inclusion and exclusion criteria were applied, more articles were disqualified because they failed to address the requirements of the paper.

Figure 2 shows the Top 20 Journals where the most relevant materials were searched and comprehensively analyzed with the Journal of Nature and IEEE leading with relevant materials that have been used.

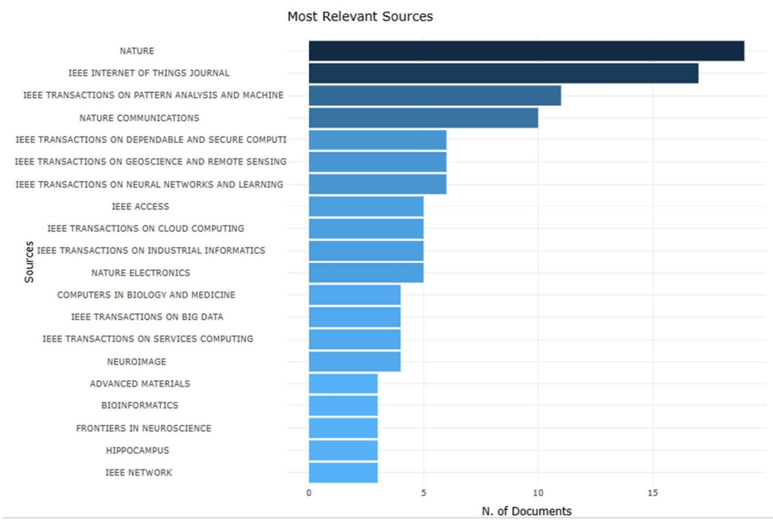

Figure 2. *Most Relevant Sources.*

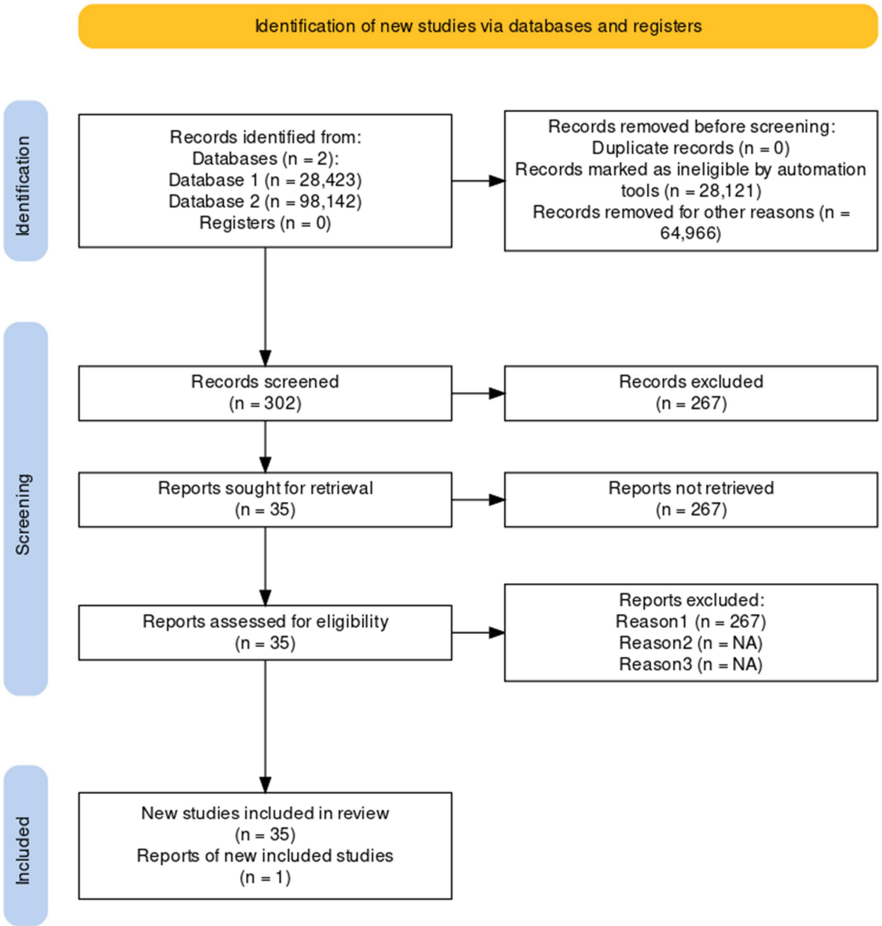

Figure 3. *PRISMA Flow chart (Haddaway et al., 2022).*

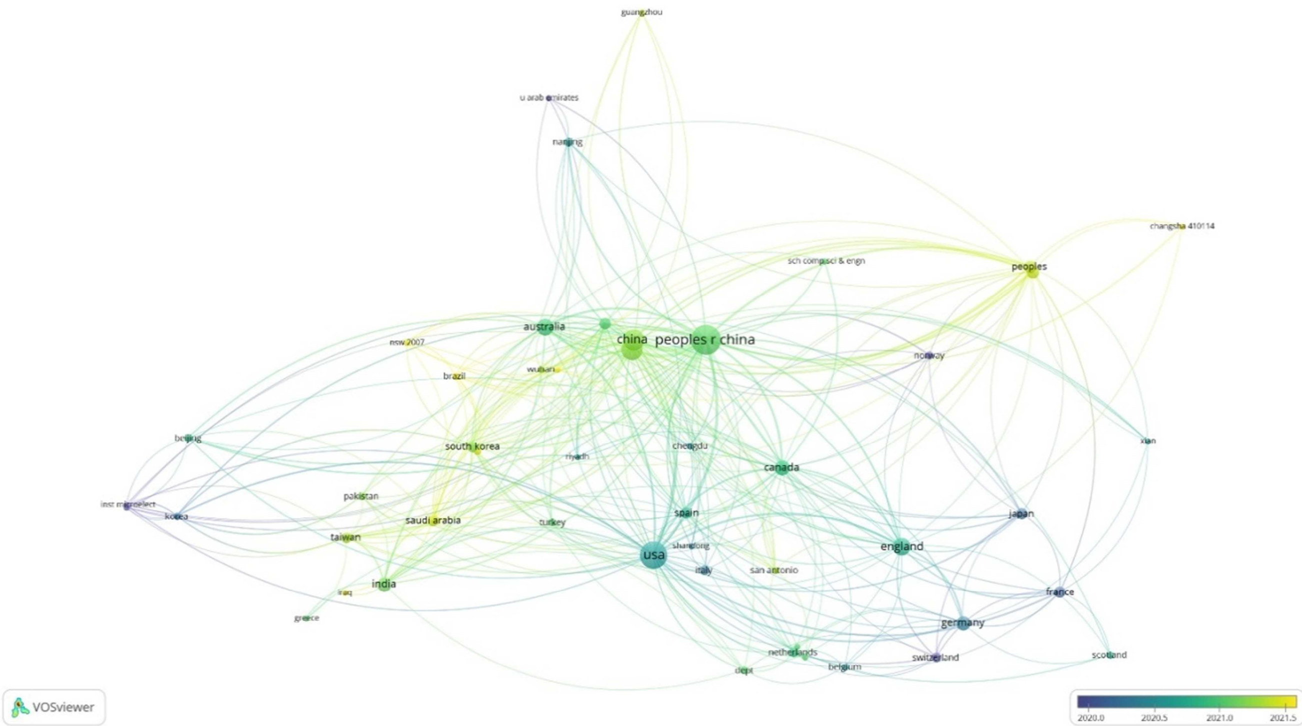

Figure 4. *Biggest country network node connected.*

Figure 4 demonstrates the level of contribution and collaboration among the Top 20 countries researching in the field of computer memory systems with the (The Group of Eight) G8 countries leading in the collaborative efforts. China, the people's Republic of China and USA are the three main countries seriously making contributions toward computer memory systems.

3. Emerging Trends

The landscape of computing technology is changing as a result of new trends in computer memory. The distinction between storage and memory is blurred by non-volatile memory (NVM) technologies like 3D XPoint and ReRAM, which promise quicker access and better data processing. The use of in-memory computing, which improves processing rates and minimizes data transmission, is growing. Advanced memory hierarchies bridge the gap between quick cache and big memory by optimizing data flow. The development of quantum computing will be aided by the coming of quantum memory. Sensitive data is protected by hardware-based encryption and secure enclaves, which improve security. Finally, machine learning activities are accelerated by memory architectures designed for AI applications. Together, these advancements open the door for computing systems that are more effective, secure, and potent.

3.1. Non-Volatile Memory (NVM)

Due to its capacity to preserve data even when the power is turned off, non-volatile memory (NVM) has become increasingly popular. This covers innovations like Flash memory, PCM, and RRAM (resistive random-access memory). Solid-state drives (SSDs) and wearables are two examples of applications that benefit from NVM's faster access times and lower power consumption compared to traditional storage [7].

3.2. High-Bandwidth Memory (HBM)

The increased need for quicker data transfer between memory and processors is met by high-bandwidth memory (HBM). When compared to conventional memory designs, HBM uses stacked memory chips that are directly coupled to a processor or GPU and offer much better bandwidth. High-performance computers, graphics-intensive applications, and data centers all benefit greatly from this technology.

3.3. Persistent Memory (PMEM)

The gap between conventional volatile memory (RAM) and non-volatile storage is filled by persistent memory (PMEM). It combines storage's data permanence with RAM's speed. Large, low-latency memory capacities are provided by technologies like Intel's Optane DC Persistent Memory, which uses 3D XPoint technology [15]. These technologies are advantageous for databases, virtualization, and analytics applications.

3.4. Quantum Memory

A developing field called quantum memory seeks to handle and store quantum data. Due to their superposition and entanglement characteristics, quantum bits, also known as qubits, may store more data than conventional bits. Building quantum computers and quantum communication systems, which promise advancements in cryptography, optimization, and simulations, requires quantum memory [13].

3.5. Memory in Artificial Intelligence (AI) and Machine Learning (ML)

Workloads for AI and ML require enormous volumes of data processing and storage. Memory innovations are essential for speeding up these workloads. Parallel processing for deep learning models is made possible by graphics processing units (GPUs) with large amounts of memory. To improve speed and decrease latency, customized memory architectures tailored for AI and ML activities are also being created.

3.6. Neuromorphic Memory

A novel strategy that draws inspiration from the neural networks of the human brain is called neuromorphic memory. Neuromorphic memory, in contrast to conventional memory systems, tries to imitate the brain's effective information processing and storage techniques. It is made to support neuromorphic computing, in which calculations are performed using concepts similar to those found in organic neurons [14].

To store and process data, neuromorphic memory makes use of non-volatile memory technologies including phase-change memory and memristors. By allowing varying resistance levels that correspond to various synaptic strengths, these memory components can simulate synapses, the connections between neurons in the brain [10].

For computations, such as pattern recognition and complicated data analysis, this method may give benefits in terms of energy efficiency and speed. Because of its distinctive architecture, neuromorphic memory is highly suited for machine learning and AI inference applications since it allows for parallel processing and effective pattern storage.

Neuromorphic memory is an area of study that has the potential to revolutionize computing paradigms and provide more brain-like and energy-efficient computer systems.

3.7. Challenges and Considerations of Computer Memory and Emerging Trends

Modern computing depends heavily on computer memory systems, yet these systems are subject to several difficulties and limitations. To retain performance, scalability must be able to handle rising memory needs. To balance great performance with minimal power usage, energy efficiency is crucial. Data protection problems include preventing flaws and unwanted access. When combining new memory technologies with current architectures, compatibility issues occur. Cost-effectiveness is still a crucial factor in the creation and uptake of memory solutions. Advancement of memory technologies and guaranteeing their seamless incorporation into a variety of computing settings depend on addressing these issues and concerns.

3.7.1. Scalability

The desire for more memory space grows as technology develops. It is difficult to ensure that memory systems can scale to meet this demand while preserving performance and lowering latency. New memory technologies like 3D XPoint and memristors are being investigated as emerging trends to address scalability difficulties.

3.7.2. Energy Efficiency

The total energy efficiency of computing systems is impacted by the substantial power consumption of traditional memory technologies. The creation of low-power memory technologies like phase-change memory and spintronics is an emerging trend. Advanced power management strategies and memory hierarchy optimizations also reduce energy usage.

3.7.3. Security

Data leaks and other memory-related problems continue to be a concern. It is essential to safeguard data kept in memory from unwanted access and threats. To improve memory security, emerging developments include hardware-based memory encryption, secure enclaves, and memory access control techniques.

3.7.4. Compatibility

The degree to which various memory technologies are compatible with current designs varies frequently. It might be difficult to effortlessly integrate new memory technologies into current systems. The development of memory interfaces and protocols that improve compatibility and interoperability across various memory types is the subject of emerging trends.

3.7.5. Cost

Modern memory technology development and production can be costly. It might be difficult to strike a balance between the price of memory components and the performance gains they provide. To reduce system costs overall, emerging initiatives include investigating more economical manufacturing methods and materials, as well as improving memory hierarchies.

In summary, scalability, energy efficiency, security, compatibility, and cost are the problems and factors to be taken into account while designing computer memory. By investigating new memory types, improving on current ones, and inventing creative solutions, emerging developments in memory technology seek to overcome these issues and build more potent and effective computing systems.

4. Future Prospects

The design and development of computer memory appear to have a bright future. Technology advancements are anticipated to lead to the development of memory solutions that are quicker, more effective, and more capable. Faster boot times and increased power efficiency may be the result of advancements in non-volatile memory technologies like Phase Change Memory (PCM) [8] and Resistive RAM (ReRAM) [7]. Advanced packaging methods and advancements in 3D-stacked memory may also aid in reducing the memory bandwidth barrier in high-performance computing. New memory technologies are raising the bar for effectiveness and performance. Data is stored using magneto resistive RAM (MRAM), which has quick read and write speed as well as non-volatility. The groundbreaking technology known as 3D XPoint, created by Intel and Micron, combines elements of RAM and storage while providing incredibly low latency and excellent endurance [16].

Memory systems will need to keep up with the demand for quicker data access and processing as data-intensive applications like AI, machine learning, and virtual reality become more widespread. More customized memory architectures that are better suited for particular tasks might result from this. With qubits possibly acting as memory units, quantum computing also opens new possibilities for memory systems. It's crucial to keep in mind that quantum memory technology is still in its infancy and confronts formidable technical obstacles.

In general, novel memory technologies, enhanced architectures, and better integration with other components are anticipated to be present in computer memory systems in the future, which will result in more potent and effective computing machines.

5. Conclusion

Computer memory, which has experienced significant advancements during its development, is a critical component of modern computing. Novel developments in-memory technology, such as non-volatile memory, high-bandwidth memory, and quantum memory, are anticipated to have a significant impact on the future of computing.

This in-depth Review includes an introduction to computer memory systems and recent trends and adheres to the PRISMA standard for literature survey. Additionally, it provides a Bibliometric study of key authors and works in the field of computer memory systems and developing trends. This review will aid in directing future research into new developments in computer memory systems. Additionally, it will direct researchers to the areas of study that require additional focus. Only new developments and computer memory systems are the subject of this study. Only research papers from two databases over the previous five years were highlighted. We will add new datasets and strategies in the future for improved direction.

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