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# A COMPREHENSIVE SURVEY OF DATA CENTER NETWORK ARCHITECTURES: DESIGN, CHALLENGES, AND EMERGING TRENDS

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*Abstract*

***Data centers (DCs) have emerged as a viable and efficient infrastructure for storing data and enabling the launch of diverse network services and applications alongside the proliferation of online applications and data volumes (e.g., cloud computing, video streaming). The underlying infrastructure is frequently burdened with the diverse resource demands (storage, computation power, bandwidth, latency) by these applications and services. The study explores various aspects of data center design, architecture, and the challenges faced by modern data center infrastructures. The paper discusses the evolution from traditional north-south traffic models to more efficient spine-leaf designs, addressing key components that enable the smooth operation of data centers. It highlights emerging trends like sustainability, edge computing, and AI-assisted management, which are reshaping the landscape of data centers to meet the growing demands of cloud computing, big data, and IoT applications. Additionally, the study examines significant challenges such as scalability, latency, energy efficiency, security threats, and network management complexities. Through a review of relevant literature, the study provides insights into current advancements in traffic scheduling algorithms, resource allocation techniques, and the integration of emerging technologies. The paper aims to provide a comprehensive understanding of the current state of data center networks, their evolution, and future trends, offering a roadmap for efficient, sustainable, and secure data center operations.***

***Keywords: Data Center Networks, Architectures, Virtualization, Scalability, Trends, Challenges, topology, Information Technology.***

## I. INTRODUCTION

The rapid growth of digital transformation has ushered in an era where the efficient management of data and computational resources is crucial for driving innovation and sustaining technological progress. Internet-based applications, ranging from search engines and video streaming platforms to social media and large-scale computations, have become integral to modern life. These applications generate massive volumes of data and rely on robust infrastructure to ensure seamless operation, scalability, and responsiveness.

At the core of this infrastructure lies the data center—a critical hub that provides the storage, computation, and networking capabilities necessary to support the ever-expanding demands of enterprises and the general public [1]. The role of data centers has evolved significantly, with cloud computing emerging as a dominant paradigm. By integrating computing and storage infrastructures, cloud computing offers a scalable, agile, and cost-effective solution to meet the diverse needs of users [2]. This evolution underscores the importance of designing data centers that are not only efficient but also adaptable to changing technological landscapes.

The design of data center network architectures is central to achieving these objectives [3]. A well-designed network topology ensures seamless communication between servers, optimizes resource utilization, and supports high levels of scalability and reconfigurability. Traditional hierarchical architectures employing top-of-rack (ToR), end-of-rack (EoR), and core switches have been widely adopted. However, these architectures face significant challenges, including bandwidth oversubscription, limited scalability, and increased latency. Addressing these challenges has become a focal point of research, leading to the exploration of novel architectures and design principles.

By analyzing the limitations of existing solutions and highlighting innovative approaches, this study provides a roadmap for developing next-generation data centers capable of meeting the dynamic demands of modern applications. Key topics include advancements in network topology [4], scalable design principles, performance optimization, and the integration of emerging technologies to shape the future of data center infrastructure.

### A. Organization of paper

Several sections make up the paper: The significance of data center networks is discussed in Section II. Section III presents the difficulties associated with data center network designs. Section IV highlights the latest trends shaping the future of data center networks. A comprehensive review of existing research related to various techniques is provided in Section V. The paper concludes with a Conclusion summarizing key findings presented in Section VI.

## II. DATA CENTER NETWORKS VIRTUALIZATION

There has been a lot of buzz lately about data centers as a cheap way to run massive service applications and store massive amounts of data. Data centers are now standard equipment for many major corporations, like Amazon, Google, Facebook, and Yahoo!, who rely on them for storage, online search, and massive computations. The growth of cloud computing has transformed data center service hosting into a multibillion-dollar industry that will be pivotal in the future of information technology (IT). These days' data centers are essential, yet their designs aren't perfect. In the past, data centers would run programs on dedicated servers, which led to low server usage and expensive operational costs.

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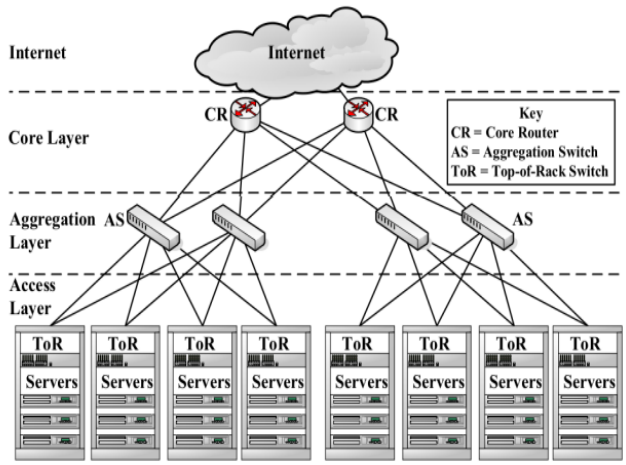


Fig.1. Conventional data center network topology

A typical data center network configuration is depicted in Figure 1. Connectivity to the servers located on every rack is provided by the ToR switch in an access layer in this topology. Particularly problematic is the fact that data center networks mostly use the antiquated TCP/IP protocol stack:

**A. No performance isolation**

There are a lot of modern cloud apps that are quite picky about latency and throughput, such as web services and search engines. In contrast, performance isolation is not available with conventional networking technologies; it merely offer best-effort delivery service.

**B. Limited management flexibility**

Many applications share servers and networks in data centers, and the owners of those applications often want to be able to monitor and manage the network fabric for things like load balancing, fault diagnostics, and security protection. Nevertheless, tenants in a data center do not have the ability to manage their communication fabric based on typical data center network designs.

**C. Increased security risks**

The communication patterns and bandwidth use of each application are not restricted by traditional data center networks. Insider threats, including performance interference and DoS assaults, might thereby exploit the network [5].

**D. Poor application deploy ability**

These days, a lot of business apps employ their own unique address spaces and protocols [6]. The need to make laborious changes to these protocols, as well as the application source code, makes migrating them to data center environments a huge challenge.

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### E. No support for network innovation

Network innovation is hindered by the rigidity of the conventional data center architecture. Because of this, it is challenging to implement changes in conventional data center networks, like adding new network services or updating network protocols. Over time, it will make the initial capital investment in data center networks less effective.

## III. DATA CENTER DESIGN & ARCHITECTURE

In the digital age, data is crucial to businesses and forms the basis of many important procedures, ranging from internal operations to customer support [7]. Typically, an on-premise IT center with servers and equipment located on-site is the best option for storing such massive amounts of data, as it aligns with both technological and business needs. Data today resides in state-of-the-art data centers, which are crucial to the rapid and massive operation of their modern society. The facilities within these data centers are developed and built with immense foresight and resources to sustain companies for decades to come.

### A. Old Data Center Design

Mainly, it relies on traffic moving north to south. The amount of hope a packet needs to reach the server was unexpected. Transferring data packets between servers used to be a very time-consuming process. Traffic going west to east is too much for us to manage.

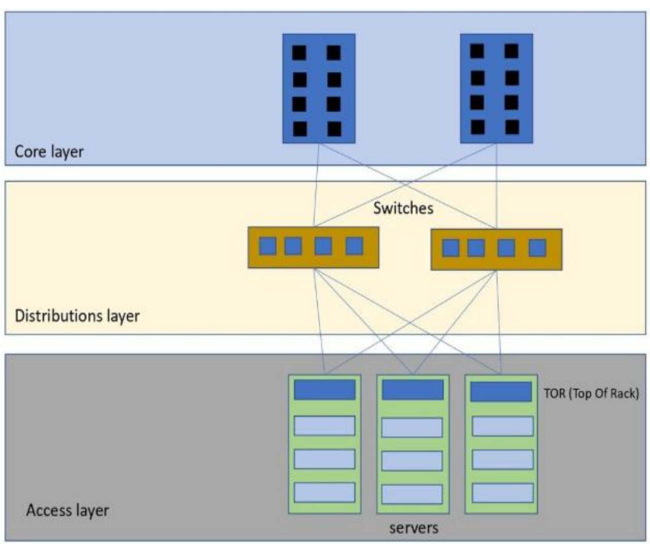


Fig.2. Old data center

### B. Data Center New Design

Alternatively, it's called a spine-leaf pattern. In the distribution layer, it makes use of large switches. [For instance, class switches from Cisco] Nodes in the spine layer are responsible for switching the distribution layer.

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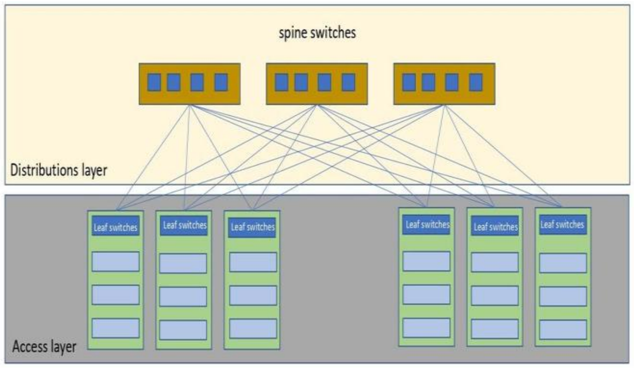

Fig.3. New data center

A leaf node is an access layer switch. The time it takes for a packet to be hopeful may now be predicted [8]. Transferring data packets between servers now takes significantly less time. A surplus of fiber optic cables. Completes east-west and north-south traffic flows.

### C. Components of Data Center

The parts that makeup data centers make it possible to store, process, and distribute massive amounts of data efficiently. [9]. These components include:

- Servers: A data center's servers are the computer programs and hardware that allow the facility to function. It allow computers to access data through connections to networks. Server racks are common places to keep servers.
- Networking: Applications and data can be stored and processed with the help of networking equipment. This equipment performs tasks such as routing, analytics, load balancing, and switching.
- Storage: The term "data center storage" refers to the hardware, software, and other components that enable data and application storage in a data center.
- Software: The software that makes up a computer system consists of all the programs, operations, and routines that are necessary for the computer to function efficiently.
- Cabling infrastructure: The cabling infrastructure is the backbone of data centers since it allows the transmission of data and electricity, which are essential to the operations. Downtime and huge costs are just two of the major consequences that can result from poorly managed systems.
- Power infrastructure: A variety of physical components are required to supply electricity to IT equipment. These include floor PDUs, remote power panels, busways, rack PDUs, and UPSs. The use of a generator to provide backup power helps keep downtime to a minimum.
- Cooling infrastructure: CRAC and CRAH units are examples of data center cooling equipment. Their purpose is to maintain the facility at an appropriate temperature and make sure that essential IT equipment doesn't become too hot.
- Physical security: To keep sensitive information and physical assets safe, data centers

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may use security systems such as biometric scanners, electronic door locks, and alarms.

### D. Data Center Design Standards

The efficiency, safety, and dependability of data center buildings can be guaranteed with the help of data center design standards. To help businesses construct data centers that are up to par with industry standards and their unique needs, several standards have been developed to outline best practices for data center construction and operation. Data center design standards that are most commonly used include:

#### 1) Uptime Institute's tier standards

The Tier Classification System developed by the Uptime Institute is among the most renowned benchmarks for the efficiency and effectiveness of data centers. Data centers are categorized into four levels according to their infrastructure and operational sustainability.

- Tier I: There is a single route for distributing power and cooling, there is no redundancy, and the availability rate is 99.671%.
- Tier II: A single route for distributing power and cooling, a few redundant parts, and an availability rate of 99.741%.
- Tier III: They have multiple active channels for power and cooling distribution, redundant components so that maintenance can happen without interruption, and an availability rate of 99.982%.
- Tier IV: Several active power and cooling distribution lines, completely redundant parts, 99.995% availability, and the ability to withstand at least one worst-case unforeseen incident without experiencing any downtime.

#### 2) ANSI/TIA-942

As an organization that develops standards, the American National Standards Institute has accredited the TIA [10][11]. An worldwide standard for redundancy and dependability, ANSI / TIA 942-A is based on the levels proposed by the Uptime Institute [12]. This standard addresses every aspect of the data center's physical infrastructure, including the design, wiring, plumbing, electrical, security, and telecommunications systems. In order to keep up with the latest technology and design concepts, it is regularly updated and made publicly available.

#### 3) BICSI-002

Full instructions for the construction and installation of data center infrastructure are provided by the Building Industry Consulting Service International (BICSI) standard. Site selection, HVAC, electrical design, space planning, and fire safety are just a few of the many topics covered in BICSI-002.

#### 4) LEED certification

The US Green Building Council (USGBC) oversees the Leadership in Energy and Environmental Design (LEED) accreditation, which assesses the environmental efficiency of

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data centers. Energy efficiency, water usage, air quality, and building materials are some of the sustainability issues that are prioritized by LEED certification.

**5) NFPA 75 and NFPA 76**

Standards for the security of computer systems and related hardware (NFPA 75) and phone systems and related infrastructure (NFPA 76) are published by the National Fire Protection Association (NFPA). All safety procedures, including fire detection and suppression, are covered by these standards.

**6) ASHRAE 90.4**

A standard for data center energy efficiency was produced by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which is known as standard 90.4. With its help, engineers may create electrical and mechanical systems that use less energy.

**7) ISO/IEC 24764**

The information technology standard ISO/IEC 24764—generic cabling systems for data centers—was created in collaboration between the IEC and the ISO. To guarantee compatibility and performance, it details requirements for the infrastructure's cabling.

## IV. CHALLENGES IN DATA CENTER NETWORK ARCHITECTURES

Data center network topology continues to be central to the communication and data transfer systems that are found in large infrastructures. However, there are numerous issues that affect data centers as technology advances. For example, power and cooling, storage, physical security, management, computing, networking, mobility, access, virtualization, and storage are some of the challenges. Below are some of the key challenges shown in Figure 4:


Fig. 4. Challenges of data center

- Scalability Issues: A typical network architecture challenges the scale of modern applications, including cloud computing, big data, and AI applications, to some extent.
- Latency and Congestion: Network utilization results to high traffic volumes due to the inadequate means of traffic routing and resource control leading to latency and congestion which are rather detrimental to real-time communications and user-experience.
- Energy Efficiency: As the energy demands of data centers go up, so does the cost of operating these centers, and the issue of sustainable energy is well worth addressing [13].
- Security Threats: Security is one of the biggest challenges and data centers are most vulnerable to data breach, DDoS attacks, and insider threats.
- Complex Network Management: Never mind the numerous components like virtual machines, containers or hybrid cloud integrations, which introduce new levels of management operational overhead and configuration error potential.
- Bandwidth Demand: The more complex and data-oriented applications such as Video on Demand, IoT, and AI create a high demand for networks that might cause delays in the networks.
- Interoperability Issues: This may create problems in compatibility whenever hardware from one vendor is used with software from a different vendor and may cause problems in efforts at repair and diagnosis.

## V. EMERGING TRENDS IN DATA CENTER NETWORK INFRASTRUCTURE

Information technology (IT) equipment and the systems that support it, including automation, electricity, cooling, telecommunications, fire systems, and security, make up data centers. Secure processing, storage, and dependable access to data is provided by these mission critical facilities [14]. Their adaptability allows for the addition of new pieces of equipment, the improvement of current pieces, the removal of old pieces, and the simultaneous use of both legacy and modern pieces of equipment. The energy usage of data centers accounts for about one percent of the total global electricity consumption. Data centers have grown in importance as a foundation for modern companies' online activities. Data center infrastructures are undergoing a dramatic shift due to the increase in data volume, the proliferation of cloud computing, the development of AI, and the fast adoption of the IoT. Data center infrastructure will continue to evolve in response to the following trends:

### A. Sustainability and Green Data Centers

Data centers are no exception to the trend toward sustainability in recent years. A major contributor to energy usage, data centers are looking to lessen their impact on the environment by converting to renewable power [15]. Green energy sources, like solar and wind power, should be integrated more seamlessly into this sector. Data centers may become more environmentally friendly with the help of new cooling solutions that save water and electricity.

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### B. Edge Computing

Fast becoming another trend in data center infrastructure is edge computing, which entails processing data closer to devices rather than just in central data centers. Reducing latency and guaranteeing quick data flow requires processing data at the edge rather than the center. This is especially important with the growing number of IoT devices[16]. Because of this, more decentralized structures are springing up in the data center industry.

### C. 5G and Data Centers

Data centers will inevitably have to change to accommodate the new network architecture brought about by the proliferation of 5G technology. The increased bandwidth decreased latency, and quicker data transfer rates made possible by 5G make it easier for data centers to handle their workloads [17]. Furthermore, data centers can take use of new possibilities brought about by 5G and edge computing.

### D. High-Density Cooling Technologies

As data center server densities continue to rise, conventional cooling methods may no longer be sufficient. This is why solutions involving high-density cooling are becoming increasingly important [18]. In comparison to air-cooled systems, liquid cooling methods allow data centers to run more efficiently, resulting in improved performance. Energy savings are another major advantage of this technology.

### E. AI-Assisted Management and Automation

There is a significant role for AI in data center management. Systems powered by AI can streamline data center operations, cut down on energy usage, and offer proactive solutions for tasks like failure prediction. On the flip side, automation solutions offer a safer and more efficient infrastructure while reducing the need for human intervention. Tools for managing data centers that use AI can sift through mountains of huge data and find ways to make incremental improvements.

### F. Modular Data Centers

The adaptability of modular data center solutions caters to companies experiencing rapid expansion. This layout facilitates the rapid expansion or contraction of the data center's infrastructure. Installing pre-manufactured modules in the field boosts deployment speed and decreases expenses. In terms of adaptability and scalability, this trend is highly advantageous.

## VI. LITERATURE REVIEW

The background research on the data center architecture based on multiple tools and techniques is provided below:

In, Shuping and Feng (2019) utilize switch cluster virtualization technology to guarantee the architecture's availability; employ Smart DNS technology (BIND 9) and Eginx reverse proxy technology to choose the closest data center across various regions, thereby reducing data transmission delays caused by physical distance. Moreover, data cannot be restored instantly following accidental destruction because a dedicated disaster-tolerant area has been established. The design is valuable and founded on ENSP simulation. Its potential for use in production deployment can be explored after making some adjustments to its model. The results demonstrate that all subnets may be unblocked, and the network topology model as a whole satisfies the criteria [19].

This study, Xu, Muqing and Guohao (2020) suggests an SDN-based traffic scheduling system that uses fuzzy logic inference. When deciding how data should travel from the controller's centralized location, the algorithm takes advantage of the features of SDN architecture, such as the separation of control and forwarding. The program begins by determining all possible paths that can be taken among the source and destination hosts. It next takes into account all possible path hops and bandwidth use. Finally, it uses a fuzzy logic model to evaluate the paths and choose the best one. According to the findings of the experiments, the suggested algorithm increases the data center's network performance by increasing throughput and enhancing load balancing, in comparison to ECMP, Hedera, and FSEM [20].

In, Eltraify, Musa and Elmirghani (2019) by enabling servers to transmit packets simultaneously in separate time slots, WDM-TDM helps alleviate congestion and oversubscription while functioning as a multiple access mechanism. Up to 75% gains in resource usage are demonstrated by the results, indicating an improvement in the architecture's provisioning and distribution of resources [21].

In this study, Sankaran and Sivalingam (2016) authors suggest an OGDCN architecture for data centers. The suggested architecture enables reachability from any route to any other route in the network without relying on rapid optical switching devices. As explained in this work, an OGDCN can be realized by combining several components. Scalability and power consumption are two metrics used to assess the framework's performance relative to competing designs. It is demonstrated that a certain OGDCN realization outperforms alternative architectures with respect to power consumption. Compared to the next best existing architecture suggested in the literature, the power usage is at least 47% lower [22].

This study, Bashir, Ohsita and Murata (2016) delves into the topic of network function virtualization and its application to the design of virtual distributed data center networks. In this design, real-world resources are partitioned into numerous virtual clusters, with an abstraction layer between each set of physical and virtual machines. The building blocks of the network are optical technologies. The method they use to build abstraction layers chooses the bare minimum of optical switches needed to link all of the machines in the cluster. The orchestration of network function chains is a primary use case of this architecture. Each chain represents a cluster, and the optical switches of the abstraction layer allow for the deployment

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of network functions [23].

This study, Mehmeri, Olmos and Monroy (2016) introduces a software and hardware architecture for data center networks that use the SDN concept and the OpenFlow/NETCONF protocols to facilitate topology control. The focus here is on the construction of an optical switching matrix based on MEMS technology, specifically on top of the SDN open-source controller Open Daylight [24].

In this study, Wang et al. (2014) explore data center network protocols, data center network interconnection topologies, and network resource sharing in multitenant cloud data centers, as well as offer a broad review and analysis of the literature encompassing a variety of study domains. They begin by providing an overview of data center networks and then navigate the designs of data center networks in accordance with their requirements. The research literature pertaining to the above listed research subjects is then presented in the parts that follow[25].
Table I provides a comparative review of various data center network architectures and approaches, highlighting their methodologies, key technologies, contributions, and limitations or future directions.

**Table I. Comparative review of data center network architectures and approaches**

| Ref | Approach | Technologies | Contributions | Limitations/Future Directions |
|---|---|---|---|---|
| Shuping and Feng (2019) | Switch cluster virtualization and Smart DNS to optimize architecture | BIND 9, Nginx reverse proxy, ENSP | Ensured availability, unblocked subnets, disaster-tolerant design, and theoretical deployment readiness | Limited to simulation; future work could focus on practical implementation and real-world testing. |
| Xu, Muqing and Guohao (2020) | Fuzzy logic-based traffic scheduling algorithm using SDN | SDN, fuzzy logic inference | Improved network throughput, load balancing, and overall data center network performance | Optimization in dynamic and large-scale networks could be explored further. |
| Eltraify, Musa, and Elmirghani (2019) | WDM-TDM technique for resolving oversubscription and congestion | WDM-TDM | Improved resource utilization by up to 75%; enabled simultaneous packet transmissions | Future work can address latency and scalability for larger networks. |
| Sankaran and Sivalingam (2016) | Optically groomed data center network (OGDCN) framework for energy efficiency | Optical grooming | Reduced power consumption by at least 47%; supported scalable, any-to-any route reachability | Needs validation in real-world large-scale deployments. |
| Bashir, Ohsita, and Murata | Virtual distributed architecture for NFV environments | NFV, optical technologies | Proposed robust resource virtualization into clusters with reduced | Scalability and cost implications of virtualization need further |

| | | | | |
|---|---|---|---|---|
| (2016) | | | optical switch usage | investigation. |
| Mehmeri, Olmos, and Monroy (2016) | SDN-based hybrid electrical/optical network topology management | SDN, OpenFlow, NETCONF, OpenDaylight, MEMS | Integrated SDN with optical technologies for enhanced topology management | Future work could focus on real-time control and management of hybrid networks. |
| Wang et al. (2014) | Overview and analysis of data center network research areas | Review studies | Provided a comprehensive understanding of interconnection, protocols, and resource sharing | Lacks experimental validation of summarized approaches; future work could explore detailed comparisons. |

## VII. CONCLUSION AND FUTURE WORK

Data centers are essential for people to get essential applications and services that fuel the world economy. Current architectures are exploited with many complications such as low efficiency, high cost and poor scalability. This study provides an in-depth analysis of data center network architectures, emphasizing the challenges such as scalability, latency, energy efficiency, and security while also exploring emerging trends like sustainability, edge computing, and AI-assisted management. It examines various innovations in network design, including software-defined networking (SDN) and resource allocation techniques that improve performance. However, the study acknowledges certain limitations, such as the complexity of integrating diverse technologies and the challenge of managing large-scale infrastructures. Additionally, the rapid evolution of emerging technologies such as 5G and IoT may require further adaptation of current network models. Future directions include developing more energy-efficient cooling technologies, enhancing the security framework to address evolving cyber threats, and optimizing network management through advanced AI-driven automation for seamless scalability and performance in increasingly complex data environments.

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