Available Online at www.ijcsmc.com

International Journal of Computer Science and Mobile Computing

A Monthly Journal of Computer Science and Information Technology

ISSN 2320–088X
IMPACT FACTOR: 7.056

IJCSMC, Vol. 13, Issue. 12, December 2024, pg.9 – 22

Enhancing Cloud Infrastructure Resilience through Kubernetes and Open Shift Cluster Management

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DOI: https://doi.org/10.47760/ijcsmc.2024.v13i12.002

Abstract: Over the last two decades, the IT sector has shifted from managing workloads on physical servers to virtualizing them and then further consolidating them into containers in the subsequent iteration. Later, Kubernetes or Open Shift were used to coordinate container workloads built on Docker and Podman. The use of containerization platforms for high-performance computing (HPC) settings, however, has been trailing behind since there is still much to learn. Containers provide flexibility, adaptability, and maintenance advantages, and they often have lower overhead. Additionally, by monitoring their performance and constantly regulating their behaviour, container orchestration platforms—which are being embraced by companies more and more—are crucial for efficiently managing the life-cycle of multi-container informatics systems. Specifically, the Kubernetes platform, a new open standard for cloud services, is helping to achieve service agnostic deployment by helping to isolate individual cloud providers via its Cloud Controller Manager mechanism. Finding the best container strategy for typical use scenarios and evaluating each solution's advantages and disadvantages were the goals. Basic performance measurements, such as average service recovery time, average transfer rate, and total number of unsuccessful calls, were gathered via a series of organized tests. Docker, Kubernetes, and Proxmox were among the container systems that were examined. Based on a thorough analysis, it can be said that the most efficient high-availability solution for widely used Linux containers is often Docker with Docker Swarm. However, there are other situations where Proxmox excels, such as when load balancing is not a crucial need or where quick data transmission is a top concern.

Keywords: Cloud Services, Critical Requirement, Cloud Controller Manager Mechanism, HPC, Kubernetes or Open Shift, Performance Metrics, High-Availability, Proxmox, Docker and Podman, Load Balancing.

I. INTRODUCTION

In contemporary IT, the transition from traditional data center architectures to more dynamic and effective models is becoming more and more important [1]. The fluctuating needs of modern workloads must be better met by traditional data centers, which usually depend on set resource allocation and architectural patterns, particularly when it comes to HPC (high-

performance computing) [1, 2]. For optimal performance, HPC has historically relied on specialized hardware and software. There are now additional options for effectively deploying and managing HPC workloads thanks to the inclusion of container orchestration systems like Kubernetes. Performance may be greatly affected by CPU hardware-assisted hypervisor characteristics, according to studies [2]. However, this does not negate the intrinsic benefits of virtual machines (VMs), such as live migration. To maximize the effectiveness of VMware v-Motion, multiple virtual machine live migration scheduling has been investigated. We are unable to do this on actual servers or containers [2].

In terms of efficiency, ideas such as VMware DRS (Distributed Resource Scheduler) may be used to schedule virtual machines to be located on the best nodes [2, 3]. The advantages of automated systems have been shown by comparisons between DRS and human specialists. It has also become more ecologically conscious and less robotic over time, particularly with capabilities like predictive DRS [3, 4]. Comparisons of the performance overheads of containers and hypervisors show that containers are more efficient. Since underlying technologies for HPC applications may greatly enhance efficiency and overhead, we wish to take advantage of this [3].

Performance has greatly increased when Docker containers are installed on virtual and bare metal computers, providing a high-performance, scalable substitute for conventional hypervisors. Containers are made more accessible by integration with DevOps and Kubernetes processes. This shift is showing its value in big businesses, despite its challenges with design, deployment, proper setup, and lifecycle management [3]. Given that containers are becoming a competitive, high-performance substitute for hypervisors, the useful advantages of container orchestration in these contexts are a comforting indication that the switch is worthwhile [3, 4].

The purpose and goals of the study are described in the introduction, which also emphasizes the importance of Kubernetes in the telecom sector and the particular difficulties associated with network traffic separation. An introduction of important technologies and ideas, including virtualization, containerization, [3, 4], NFV, and Kubernetes, is given in the background section. Information about Kubernetes networking and the functions of its main components is also included. Figure 1. The section on related work examines previous research on Kubernetes networking and pinpoints the research gap this article attempts to fill. The research questions and the particular business necessity that motivates the study are described in depth in the issue formulation section. The study procedure used to investigate the viability and performance consequences of secondary network interfaces in Kubernetes is described in the methodology section, along with the design of empirical trials, qualitative techniques, and data analysis methodologies [3, 4]. Data privacy, information security, and sustainability concerns are covered in the section on ethical and social factors. The experimental setup, including the testbed environment and the execution of Multiuse-service and Meridio proof-of-concept projects, is described in depth in the exploratory section [3, 4]. The functional and performance assessments' results are shown in the results section, which also analyses parameters like resource use, load management, latency, and throughput [3, 5].

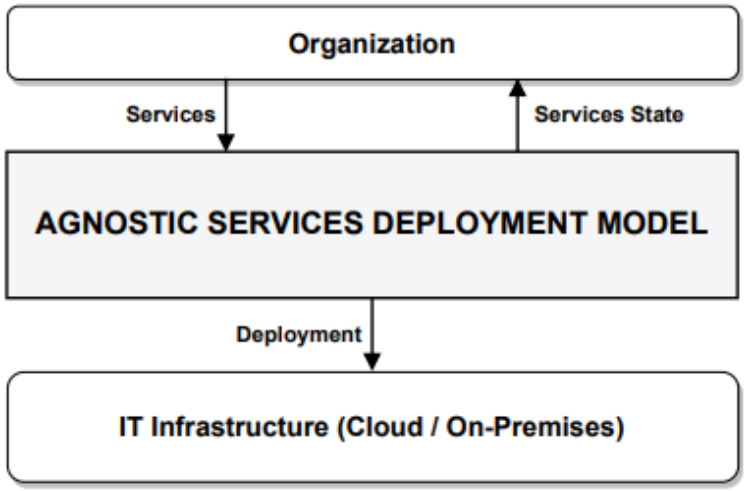

Fig. 1 Adopted strategy overview. [3]

By guaranteeing constant execution conditions, containerization may also be highly beneficial in Continuous Integration and Continuous Delivery (CI/CD) procedures, as has been investigated. Container technology supports and facilitates the migration of applications from development environments to production environments by allowing them to run under the same software versions and environment requirements, including external dependencies or libraries, irrespective of the deployment target [3, 5]. Due in large part to its control plane, the Kubernetes platform (K8s) has emerged as the de facto standard for deploying and running containerized applications (informatics systems), making it the best platform among container orchestrators for the purposes of this work [3, 5]. Additionally, the abstraction of cloud providers is made possible by Kubernetes' Cloud Controller Manager (CCM), a control plane component [5], which facilitates integration across several cloud platforms. Additionally, this method allows location transparency, which allows many Service components of a same informatics system to be distributed across several cloud infrastructures and yet function properly [5, 6].

Container technologies have been invested in by many top cloud service providers. Among them are Elastic Compute Cloud (EC2) for compute instances and Elastic Container Service (ECS), which has been used since 2017 to build Kubernetes (EKS) clusters by Amazon Web Services (AWS) [5, 6]. With a greater emphasis on consistency, durability, high availability, and scalability, Google Cloud Platform (GCP) employs Google Compute Engine (GCE) to build and operate a large number of virtual machines and makes use of Google Cloud Storage to store big data items. Additionally, GCP provides automated load balancing solutions along with high-performance networking capabilities [6, 7]. Microsoft Azure, another significant participant, offers Hyper-V containers, each of which runs within a separate virtual machine. In addition to being a well-known pioneer and active developer of Kubernetes, Red Hat's Open Shift provides more tools for the automated deployment, construction, and maintenance of container infrastructure. In order to manage clusters and allotted resources, it also offers security and monitoring tools. The adoption and development of container technologies on the Internet is assured by these significant platforms in the cloud services industry [8].

High availability, which can be defined as a combination of concepts to determine whether a computer system is available and has optimal performance, so that it does not have frequent outages and is available most of the time, guarantees that the service will remain accessible even in the event of a hardware failure or software upgrade [8, 9]. Finding and removing potential single points of failure—that is, locations at which the service either stops functioning or just functions partially—is the aim of high availability. High availability that is properly set up may also handle potential hardware and software problems. In order for the

high-availability concept to function properly, systems and services that employ it should be completely automated, meaning that no human intervention is necessary [9, 10]. They should also be able to autonomously manage performance, foresee certain failure types, and step in in the event of a catastrophic situation. Achieving high availability is also greatly aided by the problem of container system security and defines against potential threats of all kinds, from DDoS assaults to illegal access [9].

To do this, we make the assumption that a central resource orchestrator (RO) component, which serves as a first-tier scheduler to choose the most available cluster for the application's execution, is in charge of a federated architecture. In order to pick the most available worker node inside the chosen cluster, this RO works on top of local management systems (LMS) like K8s and K3S, which are run by a cluster manager functioning as a second-tier scheduler [9, 10]. The RO and the LMS are connected via the cluster management. When the expected output from the system's predictor component above a certain threshold, the cluster manager initiates the migration decision. We will differentiate between the two situations once the migration choice is made. The first one relates to the scenario in which two nodes in the same cluster migrate [10]. Container migration, or process migration in general, requires that the process state be saved and then restarted at the destination. In order to do this, we created a Kubernetes operator that makes use of the Checkpoint (2.4) functionality that was recently included into Kubernetes. Our operator builds a new image based on these checkpoints, uploads the newly constructed image to an image registry [9, 10], and strategically creates checkpoints for stately containers (which capture the entire state of the container, including its working memory, process state, open files, and other critical system resources) [8, 9].

An open-source platform called Kubernetes, also referred to as K8s, is used to automate the deployment, scaling, and administration of containerized applications [10]. It has grown to be the most popular container orchestration solution in the market because to its many capabilities that facilitate the seamless deployment of applications by developers and system administrators. The intricate design of Kubernetes allows it to smoothly combine several components. Kubernetes has served as the foundation for or inspiration for a number of container orchestration solutions. For example, its community distributions, Red Hat Open Shift and OKD [10,11], are built on top of Kubernetes, adding features and expanding its capability. However, Kubernetes serves as the inspiration for technologies like KubeEdge and K3s, which are designed to be lighter and more appropriate for edge computing situations [11]. Specifically, K3s is made to provide a simplified version of Kubernetes that is simpler to set up and administer at the network's edge.

Several containerization platform options are examined in this study, including Proxmox, which utilizes LXC technology, Kubernetes, which uses the CRI-O container interface, and Docker, which uses Docker Swarm, which uses Containerd technology [1]. The emphasis is on the key features of the systems, including the average call duration, the frequency of unsuccessful calls, the rate of data delivery to the user, and the recovery time of service availability. In addition to an analysis of the test results, the article suggests test scenarios that are used to evaluate these services [2, 9].

The comparative study and performance assessment of high-availability solutions in Linux container systems are what make the article unique. This article especially focuses on assessing the performance characteristics of various high-availability systems, even if other studies include diverse facets of container technologies as virtualization, orchestration, security, and containerization. Through trials and result analysis, it closes a gap in the literature by providing comprehensive statistics on data transfer rate, average call time, unsuccessful calls, [4, 5], and service recovery time for well-known container systems Docker, [5], Kubernetes, and Proxmox. With the help of this new addition, readers may choose the best high-availability solution for their particular use cases with knowledge.

II. RELATED WORK

(Kovač, M., 2024) Over the last two decades, the IT sector has shifted from managing workloads on physical servers to virtualizing them and then further consolidating them into containers in the subsequent iteration [5, 6]. Next, Kubernetes or Open Shift were used to coordinate and automate container workloads that relied on Docker and Podman as the underlying container technologies. However, since there is still more work to be done to determine how to implement containerization platforms for HPC in practical situations, high-performance computing (HPC) environments have been trailing behind in that process [5, 9]. In general, container technologies like Kubernetes and Open Shift require a lot less overhead from a compute standpoint while offering several advantages in terms of flexibility, modularity, [9, 10], and maintenance. They are thus perfect for jobs needing a lot of processing power.

(Vallabhaneni, G. N. 2021) Through the internet, cloud computing gives businesses access to computer resources (hardware or software). Cloud service providers allow enterprises to subscribe to computing resources such as servers, networking hardware, databases, storage, and software [5]. Cloud service providers enable businesses to pay for the resources they use and expand their computer capabilities as needed. Businesses may lease access to software and storage from a cloud service provider rather of owning their computer infrastructure or data canters. It assists companies in reducing their infrastructure capital expenditures. The pay-as-you-go approach of cloud computing is advantageous to the majority of businesses. (According to the introduction.) *Date of publication unknown [4, 6].

The high availability of applications hosted on container platforms is still widely unknown, despite the fact that several other performance evaluations of orchestration techniques and containerization settings have been carried out [6, 7]. This research aims to close this gap by demonstrating which of the containerization technologies being studied may be used to provide the highest possible degree of high availability.

III. MATERIAL AND METHOD

Applications and processes may run independently of the host operating system thanks to Linux containers, which provide isolated environments. Applications may operate in separate contexts using containerization, a kind of operating system virtualization, instead of requiring the complete virtualization of the operating system [6, 7]. Containers provide application portability, compatibility, and independence from particular operating systems by encapsulating all required dependencies and application files. Compact size and improved mobility are characteristics of containers, especially those used in cloud systems [6, 7]. This implies that without needing changes to the application code, programs created for one operating system may run well on another. Operating system-level virtualization is utilized to provide high availability in containerized solutions [4, 6], enabling the simultaneous operation of many Linux systems. Containers function without the requirement for an extra virtualization hypervisor, in contrast to systems that depend on one [6].

3.1 LXC and Proxmox as a Container Orchestrator

LXC is one of the tools used in container virtualization. Multiple isolated containers may operate and virtualize concurrently thanks to this operating system-level virtualization. Without starting a virtual computer, LXC limits and prioritizes system resources using the Linux system's characteristics [6, 7]. Through the use of namespaces, a specific container's access inside the operating system may be isolated, separating the ownership of the container files from that of the operating system files [8].

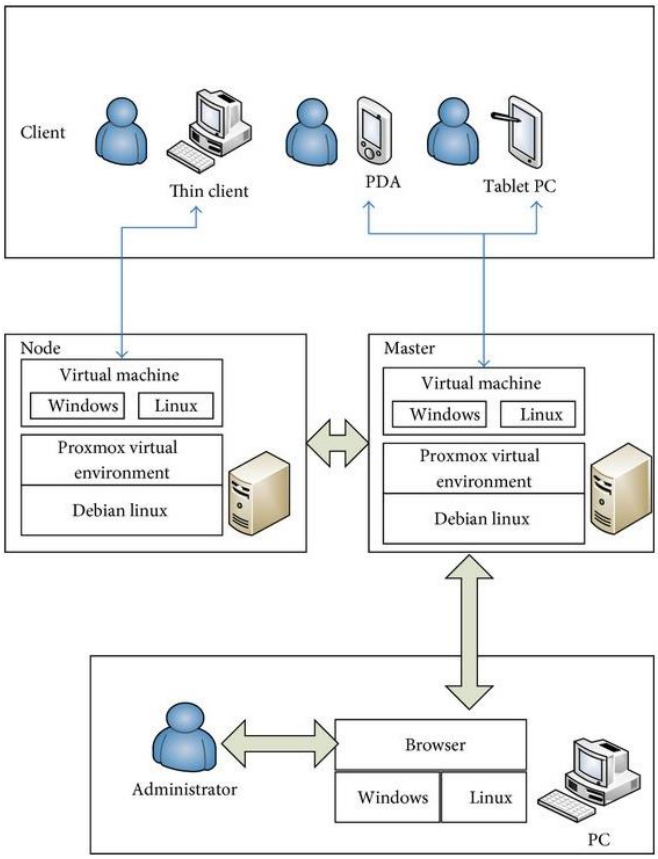

Fig. 2 Proxmox Virtual Environment Architecture. [8, 9]

3.2 Containerd, Docker, and Docker Swarm as a Container Orchestrator

The OS-specific system calls and functions required to execute and virtualize containers are separated by the abstraction layer known as containerd [9]. To avoid requiring users to deal directly with system calls, it offers functions that are abstracted and simplified. The superstructures above it are in charge of managing network components and settings, which containerd cannot handle [9, 10]. The foundation of Containerd is an API that enables container management and access [10].

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IV. RESULTS

The Proxmox VE platform generally takes the longest time to recover a node, according to the analysis of the experiment results, which showed that the service recovery time was best in the first scenario. This test was repeated ten times for each of the installed services and configurations [12]. The fencing mechanism, which the Proxmox platform does to recover the service, is probably the cause of this lag. It aims to restore the lost node first, after which it transfers it to another computer on that node [12]. Overall, the Docker environment and its high-availability manager, Docker Swarm, had the quickest service recovery (see Figure 2 [11]). Due to its usage of the CRI-O intermediate and higher overhead services, Kubernetes only managed to finish second in terms of service recovery speed. By default, the service

recovery rate may be impacted by the extra communication and processing that comes with using CRI-O as an intermediary layer.

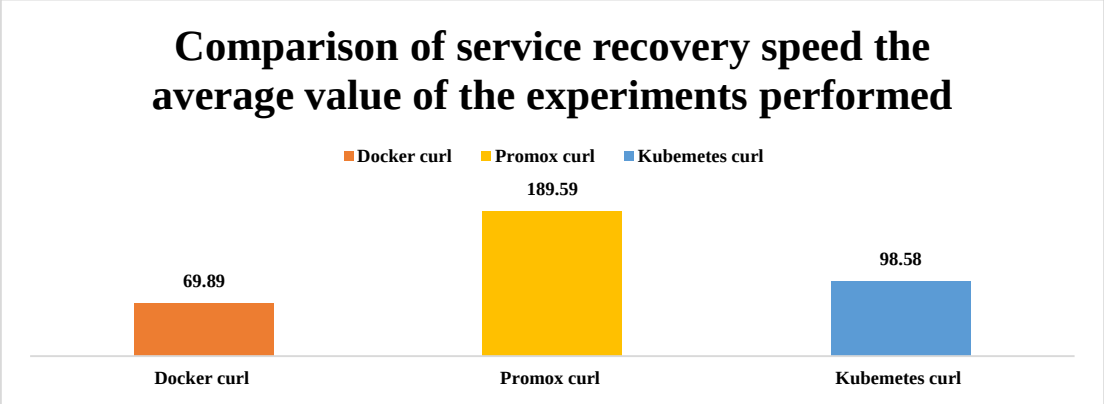

Fig. 3 Measuring the services recovery rate. [13]

The Kubernetes platform with a single node had the most failed calls, according to the analysis of the results from the experiments conducted using the second scenario, which focused on the total number of failed calls [14]. The total number of failed calls increased linearly on this service [15]. On the other hand, the Docker platform, which uses up to three nodes and has a high-availability manager called Docker Swarm, had the fewest failures. The Docker platform performed somewhat worse than the Proxmox platform when employing a single node; Figure 3 [15] shows that Proxmox had an average overall failure rate in the center of all platform assessments.

The data rate analysis was an additional investigation based on the second scenario using Apache Bench. The Proxmox platform had the greatest average data transfer rate, meaning it was able to move the most data in a certain period of time, according to the analysis's findings [16, 17]. With a single node having the poorest average data transmission rate, the Kubernetes platform had the worst overall result [18]. Nonetheless, the services were comparatively balanced, irrespective of their overall number of nodes. The table, which is separated into columns with an increasing number of concurrent calls and total calls for each platform, provides an interpretation of the data. The mean of the outcomes from every column in a row is shown in the last column. Table 1 displays individual findings for data rates in kilobytes per second [19].

Table 1. Transfer rate measurement in kilobytes per second. [19, 20]

Simultaneous call/Total Number of Calls	5/10	50/100	500/1000	5000/10,000	5000/50,000	Mean
Docker single node	546.96	896.65	896.65	87.96	249.59	514.59
Docker three nodes	489.69	1236.54	696.56	132.22	263.36	452.69
Proxmox	341,489.69	654.59	489.59	489.99	156.59	542.96
Kubernetes single nodes	635.55	526.65	145.65	296.58	549.65	596.54
Kubernetes three nodes	496.59	686.96	246.59	698.58	512.69	549.58

The best appropriate high-availability solution in terms of performance in widely used Linux containers is Docker with the Docker Swarm high-availability manager, according to the analysis of the findings from all the trials [20]. Proxmox is the best platform if the transfer rate is the most crucial factor. Though one must consider its average call time results, which are noticeably worse than those of the other platforms [23], Proxmox is once again the best option if one does not intend to use a load balancing service and it is crucial to have as few total failed calls as possible [20, 23]. Although Kubernetes may not have always produced the best results, its competitive performance in important metrics, including average recovery rate, average call time, and average failed calls, [23] shows that it has the potential to be a

strong and dependable high-availability solution in particular situations. In brief the combined outcomes of each trial are shown in Table 2 [22].

Table 2. An overview of the findings from each experiment. [23]

	KB/b	Milliseconds	No.	Seconds
Technologies	Average Transfer rate	Average Call time	Average Failed Calls	Average Recovery rate
Docker	514.59	4895.66	216.52	69.65[1]
Proxmox	26,6259.96[1]	4150.65[2]	152.52[2]	65.69
Kubernetes	540.21[2]	5496.65	249.52	123.26[2]
Docker 3 Nodes	596.18	2963.64[1]	14.56[1]	-X
Kubernetes 3 Nodes	526.59	3652.59	26.36	-

V. DISCUSSION

The performance parameters of several high-availability solutions for Linux containers are usefully detailed in this paper [24]. Making educated decisions while choosing the best high-availability solution for certain use cases is made possible by comparing several services according to factors like average call duration, data rate, total number of unsuccessful calls, service recovery time, and [25]. A dependable and effective container-based infrastructure may be ensured by making the best choice possible by being aware of each service's advantages and disadvantages [14].

The research also emphasizes how crucial it is to consider the unique needs and features of any application or service that is implemented, in addition to performance metrics. Resource, scalability, and fault tolerance needs might vary depending on the application [12]. Therefore, before choosing a container platform, it is crucial for enterprises to properly evaluate their unique demands [14, 16].

a thorough evaluation of the various convergence architectures, including gVisor, Kata, Firecracker, QEMU/KVM, and Docker. CPU, RAM, system calls, network, disk storage, and startup time are among the performance parameters it examines [18, 20]. The findings point out performance constraints and trade-offs associated with virtualization and provide guidance for case-specific decision-making.

Malviya and Dwivedi, the authors, compared Redhat OpenShift, Mesos, Docker Swarm, and Kubernetes, four container orchestration solutions. Security, deployment, cluster installation, scalability, stability, and learning curve are among the characteristics taken into account during evaluation [20, 25]. The results indicate that Mesos is appropriate for scalable deployments, Open Shift is superior in security, Docker Swarm is user-friendly, and Kubernetes offers the finest scheduling functionality. Of the systems mentioned, Kubernetes is the most widely used technology.

VI. CONCLUSION

In this research, a new infrastructure for managing HPC systems based on Kubernetes is proposed. Additionally, it covers a wide variety of issues pertaining to orchestration, virtualization, containerization, and HPC. After talking about the intricacies of HPC, we came to the conclusion that Kubernetes and containers are complicated and should be made as simple as possible for HPC workloads. The comparison and study of several high-availability solutions for Linux container infrastructures were the main topics of the paper. Data on the average number of unsuccessful calls, average quantity of data transmitted, and average service recovery time were gathered based on the trials conducted. With the use of these data, it was possible to evaluate each solution's advantages and disadvantages and choose the best container option for widespread usage.

According to an analysis of the tests, Kubernetes came in second place and Docker, with its high-availability manager Docker Swarm, fared best in terms of the quickest service recovery. However, in the service recovery speed test, the Proxmox platform performed the

poorest. The Proxmox platform was the best service when the load balancing function of Docker and Kubernetes was not employed, but the Docker platform with its high-availability manager, Docker Swarm, was once again in the lead for the number of unsuccessful calls.
The viability and performance effects of providing services via secondary network interfaces in Kubernetes are examined in this study. The original impetus came from conversations about using Kubernetes in their cloud-native environment inside Ericsson Cloud-RAN, where one of the challenges was traffic separation. Future studies will compare various forms of persistent storage in terms of performance, availability, scalability, and security, as well as examine the most recent security procedures and safeguards for container settings. Reducing expenses while enhancing container applications' availability and dependability is another crucial objective. In order to effectively manage high availability in demanding and dynamic container systems, research should concentrate on novel ways. Future research might potentially use clustering techniques and artificial intelligence to enhance the security, administration, and performance of container systems.

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