Parikshan: A Testing Harness for In-Vivo Sandbox Testing

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ABSTRACT

One of the biggest problems faced by developers testing large scale systems is replicating the deployed environment to figure out errors. In recent years there has been a lot of work in record-and-replay systems which captures traces from live production systems, and replays them. However, most such record-replay systems have a high recording overhead and are still not practical to be used in production environments without paying a penalty in terms of overhead.

In this work we present a testing harness for production systems which allows us to run test-cases in a sandbox environment in the wild at any point in the execution of a service oriented application. The paper levarages, User-Space Containers(OpenVZ/LXCs) to launch test instances in a container cloned and migrated from a running instances of an application. The test-container provides a sandbox environment, for safe execution of test-cases provided by the users without any perturbation to the execution environment. Test cases are initiated using user-defined probe points which launch test-cases using the execution context of the probe point. Our sandboxes provide a seperate namespace for the processes executing the test cases, replicate and copy inputs to the parent application, safetly discard all outputs, and manage the file system such that existing and newly created file descriptors are safetly managed.

We believe our tool provides a mechanism for practical testing of large scale multi-tier and cloud applications. In our evaluation provide a number of use-cases to show the utility of our tool.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; D.2.8 [**Software Engineering**]: Metrics—*complexity measures, performance measures*

General Terms

Theory

Keywords

ACM proceedings, LaTeX, text tagging

1. INTRODUCTION

As application software grows and gets more complicated, testing large scale applications has become increasingly important. The recent trend towards DevOps[3] by the software engineering industry further compounds this problem by requiring a fast and rapid resolution towards any software bug. DevOps stresses on close coupling between software developers and operators, and to merge the operations of both. Most of these companies have very frequent releases and hence require a very short time to a bug fix, test, patch and release in order to realize continuous delivery(Facebook mobile has 2 releases a day, and Flickr has 10 deployment cycles per day).

However, it is extremely difficult to meet the quick debugging demands of a devops environment, as it is not feasible to recreate realistic workloads in an offline development environment for large scale multi-tier or cloud based applications. In general, testing in the development environment can be (1). Un-realistic because it may not be possible to faithfully reconstruct the production environment, (2). Incomplete, as it may be impossible to generate all possible input cases (3). Costly, as it is infeasible to test all possible configurations given time and cost constraints of releasing the software to the field. Hence testing is not only difficult because of difficulty to recreate production scenarios, it is also increasingly important to test and catch bugs in a very short period of time.

One of the proposed mechanisms of addressing this problem is to "perpetually test"[**?**] the application in the field after it has been deployed. This is important since testing in a production system enables us to capture previously "unreachable" system states, which can arise due to various factors such as unpredictible user environment, outdated softwares, an ever increasing list of hardware devices (e.g. mobile phones, embedded devices etc.), or simply because of imperfect network connectivity (wifi, cellular). Some approaches such as Chaos Monkey[**?**] from Netflix, and AB Testing[**?**] already use "testing in the wild" to check for errors and robustness of the software, or to check for new features that have been added. However, despite a clear need, testing in the wild has never gotten much traction in real-world applications as it consumes too much performance bandwidth and more importantly, it can affect the sanity[1] of real operational state of the software.

The motivation behind our work is to provide "testing as a service" for real-time diagnosis of production applications in order to signifcantly reduce the time towards bug resolution. We observe that most modern day service oriented applications are hosted on IAAS cloud providers, and can hence be easily scaled up. Leveraging this abundance of resources, and recent advances in user-space virtualization technology(OpenVZ/LXC[1, **?**]) we present a testing mechanism which allows the user to dynamically insert test cases in a production environment(we call this in-vivo testing), enabling real-time diagnosis.

Our system called `Parikshan`[2] allows capturing the context of application, and for tests to be run without effecting the sanctity and performance of the actual user-facing application. This is done by cloning a production server and creating two containers: a production container, and a testing container. We duplicate the incoming traffic to both the production container and the test container using a custom proxy, which ignores the responses from the test-container. The testing on the test-container is done on the fly using dynamic instrumentation, hence any set of test-cases can be turned on whenever required. The user can pre-define probe points for dynamically inserting test-cases (by default the entry and exit of each function is considered a probe point). Since the test is executed in a VM it acts like a sandbox which restricts it from causing any perturbation to the state of the parent process, or effecting the sanity of the responses to the production client. We synchronize the production and test containers using a variant of live migration without suspending the services of the production server, and follow it up with frequent synchronization for a long running tests.

The key contributions of this paper are:

- A tool which provides a sandbox environment to execute test cases in the production environment. This allows for a safe and secure test harness which does not effect the production state, and allows the application to proceed in it's execution.

- We allow for dynamic insertion of the test case, and safetly capturing the context of the application. Dynamically inserting test-cases is important to avoid relaunching binaries in the test-container with the required test-cases. Restarting binaries is not possible, because it would break active network connections, and destroy the state of the test container

- Language and Platform agnostic: One of the key advantages of our approach is that it is language and platform agnostic. Since the underlying mechanism takes advantage of containers as a platform to do the cloning, the language or interface does not matter as far as cloning is concerned. Of-course testing mechanims may differ depending upon different languages.

1.1 Impact

The impact of sandbox testing can be seen in several different ways

- **Monitoring Applications/Localized Errors** Most user-end applications have monitoring mechanisms to capture the health of the application built within the system. Such monitoring mechanisms can often indicate problems in the systems showing spikes or slowdown in CPU usage, memory footprint, cache misses etc. Very often problems in stable production systems are either (1) restricted to only a small percentage of transactions, (2) are system wide, but have minimal effect on the user (cumulative effect of slow memory leak etc.). Such problems often do not necessitate taking down the system or lead to a crash *Parikshan* can be used to do a live analysis from the point of time when the clone is done, with much deeper monitoring, and light weight testing to localize the errors without worrying about the slowdown to the production system.

- **Fault Tolerance Testing** A possible implementation of the *Parikshan* test harness is to do Fault Tolerance Testing. As mentioned earlier testing and recreating large-scale configurations is extremely difficult. Additionally testing scalable aspects is costly as a significantly large test-bed is required to replicate loads. Recent large scale fault tolerance testing approaches has been to use fault injection at random places. One such example is Chaos Monkey[**?**] which has been employed by Netflix [**?**] video streaming service. Netflix has a highly distributed architecture with a large client base, and has several robustness mechanisms inbuilt to manage for failure. The chaos monkey infrastructure forces random failiure in live Netflix production servers, to test it's fault tolerance. The key intuition behind this approach is, that faults in an ever evolving large-scale environment are inevitable, and in most cases the infrastructure will be able to auto-respond and get its instances back to a live state. However, in the cases when it is unable to do so, Netflix wants to learn from failures, by forcing them in scheduled low-traffic hours.

  Natrually such in production fault-injection mechanisms will always effect the user. An alternate mechanism proposed by *Parikshan* is to use the test-container to inject faults. As a clone of the production-container any fault-injected should produce a similar effect as the original container, without effecting the user.

- **Testing Software Updates - AB Testing** Software patches for performance or functional updates are frequently done on backend servers. These may not necessarily change the user-facing input and can be optimizations internal in the back-end server. Such patches can be first tested in the test-container to verify that they are correctly behaving before doing the release. A similar approach called A/B Testing[**?**] is commonly used in mobile and web-applications, which randomly forwards a small percentage of user traffic to a backend server B a modified version of the backend server(A is the original server). This gives the developer a controlled experiment scenario where he can see if the updates work without effecting too many users. *Parikshan* can potentially extend this by testing all user input since it does not effect the user experience at all.

[1]The state of the production server may change leading to a crash or wrong output
[2]Parikshan is the sanskrit word for testing

- **Verification**

2. MOTIVATION

2.1 Motivationg Scenario

Take for example user Joe who is an administrator, and IT manager for a multi-tiered system. Much like several IT systems user Joe has a dashboard which informs him of the health status of all of his applications, and provides him with high level statistical views of all tiers of the system. At time t0, Joe observes an unusually high memory usage by tierA for transaction type X or unusually high latencies in fetch operations for user Y. Under usual circumstances, the system would have to go down(depending on the severity of the problem), a ticket would be generated for the developer and the system would be patched once the problem has been diagnosed. However often, it is difficult to find out the confiugration of the system, and the user input which is causing this problem, also solving any emergent problems as soon as possible is extremely important.

Joe can now use *Parikshan*, to fork off a clone of tierA as test-tierA. Our proxy balancer sends a copy of the incoming request to test-tierA, while users can continue using tierA. Process in test-tierA follow the same execution paths, as they receive the same input(we discuss non-determinisim related issues later); this allows Joe to initiate deeper test-cases, and observe the test-tierA, without fearing any problems in the user-facing operations.

Time to bug resolution is usually a very important criteria in any user-facing service oriented application. Bearing this in my mind we believe, that online testing will be an important aspect towards modern applications. Additionally the usage of redundant computing for testing in alpha-beta testing(see 3) approaches is a well accepted paradigm in real-world applications. This leads us to believe that using redundant computing should be acceptable for regular testing approaches as well.

2.2 Motivation Questions?

To further motivate our testing paradigm we have come up with a set of motivating questions:

2.2.1 **Q1:** *Is it persistent testing important?*

2.2.2 **Q2:** *Is recreating production environment difficult?*

2.2.3 **Q3:** *Can redundant computing be utilized for testing?*

2.2.4 **Q4:** *How would executing test-cases in a production server effect user-experience?*

3. RELATED WORK

There have been several existing approaches that look into testing applications in the wild. The related work can be divided in several categories:

- **Perpetual Testing** We are inspired by the notion of perpetual testing[?] which advocates that software testing should be key part of the deployment phase and not just restricted to the development phase.

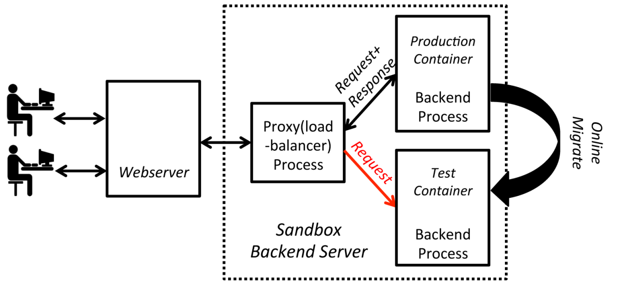

Figure 1: Backend wrapped around with Parakishan Run-time

- **Record and Replay**
- **Alpha-Beta Testing**
- **DevOps**

4. DESIGN

4.1 System Overview

Each instance of *Parikshan* can target only one tier at a time. However, multiple instances can be orchestrated together especially when it's required for integration testing or cross tier results need to be correlated. To begin with let us look at a simple example of client webserver with a database server as the backend (as shown in Figure 1), where the test harness needs to be applied on the backend. As explained earlier basic workflow of our system is to duplicate all network requests to the production backend server and a "live cloned" test container. Traffic duplication is managed by our proxy network duplicator (see section 4.3), which uses several different strategies to clone user input to our test-container, with minimal impact on the production container. Another core aspect of our design is how to implement "live cloning"; this is the process by which a production container (in this case our backend service), can be cloned to create a test-container which has the same file system and process state. Cloning and syncing between the production container and the test-container is managed by our clone manager, which uses user-space containers OpenVZ and a variant of live migration to manage the cloning. Next, we explain each of the modules in detail.

4.2 Clone Manager

While the focus of our work is not to support VM Container migration, or to make changes to the hypervisor, we need to tweak the way typical hypervisors offer live migration for our purposes. Before moving further we wish to clarify that instead of the standard live migration supported by hypervisors, *Parikshan* requires a cloning functionality. In contrast with live migration, where a container is copied to a target destination, and then the original container is destroyed, the cloning process requires both containers to be actively running, and be still attached to the original network. This cloning requires some tweaking, and modification in both how compute migration is handled, and especially how the network migration is handled.

To understand cloning in our context, let us understand how live migration works. Live migration refers to the process of moving a running virtual machine, guest os or container from one host node(physical machine) to another, without disconnecting any client or process running within the machine. Live migration is supported by most well known Hypervisors(vmware, virtualbox, xen, qemu, kvm) with different amount of efficiency. There are several variants of migration, some of which require a short suspend time, while others are able to seamlessly transfer without any noticeable down-time by the user. In general the process involves the following steps: (1) Firstly, the copy (*rsync*) is initiated by a pre-copy memory migration, where the underlying hypervisor copies all the memory pages from the source to the destination. (2) Once pre-copy phase is finished, the VM is temporarily suspended, and all memory pages including live memory pages are transferred to the target node. Once all memory pages have been transferred the target container is restarted. Obviously, two rsync runs are needed, so the first one moves most of the data, while the container is still up and running, and the second one moves the changes made during the time period between the first rsync run and the VM stop [3].

Instead of Live Migration, in Live Cloning, we do not suspend operations of the source container, rather we allow the container to keep executing in both production and test locations. The more tricky aspect is that there are two containers with the same identities in the network and application domain. This is important, as the operating system and the process may be configured with the IP Address, or other networking operation, which cannot be changed without leading to a crash of the system. Hence the same network identifier should map to two seperate addresses. Clearly the same ipAddress, mac addresses cannot be kept for both the production and test-container as that would lead to conflict in the network. There are two ways to resolve this : (1) Host each container behind their own network namespaces, on the same host machine, and configure packet forwarding to both containers such that the duplicator can communicate to them. Network namespaces is a definete possiblity, and have been used by several hosting providers, to launch VM's with same private ipAddress, in a shared network domain [**?**]. (2) Another approach is to host both containers in different machines with port forwarding setup to forward incoming TCP requests to containers behind a NAT. This is slightly more scalable and has clear seperation of network and compute resources. However, an obvious downside to this approach is that it needs a new VM to be allocated. As of now, we have implemented the second approach for our proof of concept mostly because of the ease of implementation.

4.2.1 Cloning Modes

Test Containers and production containers can be allocated in various schemes: we call these schemes *modes* Broadly speaking the clone manager works in 2 modes :

- *Internal Mode*: In this mode we allocate the test-container and production containers to the same host node. This would mean less suspend time, as the production container can be locally cloned (instead of streaming over the network). Requires the same amount of resources as the original production container (number of host nodes remain the same), hence could potentially be cost-effective. On the down-side, co-hosting the test and production containers, could have an adverse effect on the performance of the production container, hence effecting the user.

- *External Mode*: In this mode we provision an extra VM as the host of our test-container (this VM can host more than one test-containers), While this mechanism can have a higher overhead in terms of suspend time (3 seconds, dependent on process state), and it will require provisioning an extra host-node, the advantage of this mechanism is that once cloned, the VM is totally seperate and will not effect the performance of the production-container. We believe that such a mode will be more benificial in comparison to the internal mode, as testing is likely to be transient, and it is often more important to not effect user experience[4].

[3]Network migration is managed by the IAAS which publishes the same MAC address for the copied VM. Since the identity of the target container remains the same, the IAAS is able to give it same IP Address, and network traffic is rerouted after the identity is published in the network

4.2.2 Implementation

In our current implementation, we are using OpenVZ[1] as our container engine, and have modified the migration mechanism in vzctl [2] to make it work for live cloning instead. We tested this out on multiple VM's acting as host nodes for OpenVZ containers. To make the cloning easier and faster, we used OpenVZ's *ploop* devices [**?**] to host the containers. *Ploop* devices are a variant of disk loopback devices where the entire file system of the container is stored as a single file. This makes features such as syncing, moving, snapshots, backups and easy seperation of inodes of each container file system.

The algorithm for live cloning is explained below:

Algorithm 1 Algorithm for Live Cloning using OpenVZ

```
1. Safety Checks(Checks that a destination server is available via ssh w/o entering a password, and version checking of OpenVZ running in it)
2. Runs rsync of container file system (ploop device) to the destination server
3. Checkpoints and suspend the container
4. Runs a second rsync of the ploop device to the destination
5. Start container locally
6. Set up port forwarding and packet duplication
7. Starts the container on the destination
```

[4]*Scaled Mode*: This can be viewed as a variant of the External Mode, where we can scale out test-containers to several testing containers which can be used to do statistical testing and distribute the instrumentation load to capture the overhead easier. This reduces the frequency with which the container needs to be synced. This is currently out of the scope of this paper, however we aim to show this in a future publication.

Iteration	1	2	3	4	5	Avg
Suspend + Dump	0.60	0.60	0.57	0.74	0.59	0.65
Pcopy after suspend	0.60	0.60	0.57	0.74	0.59	0.65
Copy Dump File	0.60	0.60	0.57	0.74	0.59	0.65
Undump and Resume	0.60	0.60	0.57	0.74	0.59	0.65
Total Suspend Time	0.60	0.60	0.57	0.74	0.59	0.65

Table 1: Performance of Live Cloning (external mode) with a random file dump process running in the container

Let us imaging we are cloning production container C1 on Host H1 as test container C2 on Host H2. The initial setup requires certain safety checks and pre-setup to ensure easy cloning, these include: ssh-copy-id operation for accessing without password, checking pre-existing container ID's, check version of vzctl etc. These ensure that H1 and H2 are compatible, and ready for live-cloning. Next, we run an intial rsync of container C1, from Host H1 to Host H2, this step does not require any suspension of C1, and copies the bulk of the container file system to the destination server (H2). The next step involves checkpointing, and dumping the process in memory state to a file, this is what allows the container to be restarted from the same checkpointed state. However for sanity of the container process, it is important to restart the container from the same file system state as it was when the checkpoint was taken. To ensure this, we take a second rsync of the ploop device of C1, and sync it with H2, after this the original container can be restarted. Next we copy the dump file from step 3, from H1 to H2, and resume a new container from that dump file.

Clearly the overhead of live migration depends on the I/O operations happening within the container between step 2 and step 4 (the first and the second rsync), as this will directly impact the amount of memory that needs to be copied during the suspend phase. A few iteration of cloning a container back and forth between two OpenVZ instances (on KVM's within the same physical machine), resulted in an average suspend time of 1.8 seconds for the production container, and 3.3 seconds for launch of the test-container(see table 1). This is nearly the same as that of native live migration, and has lesser suspend time for the production container as we do not include the *"copy dump file"*, or the *"undump and resume phase"* for production containers.

4.3 Proxy Network Duplicator

As described earlier an important aspect of live cloning is that we have two replicas which share the same identity. While we do not have strong consistency requirements, in order for both containers to execute they must receive the same input. This can be achieved in multiple ways, the easiest would be a port-mirroring mechanism either using software provided tap devices or in hardware switches (several vendors provide mirroring options). These are both pretty common, and are blackbox and do not require much configuration. However, such port mirroring solution gives us minimal control on the traffic going to our test container.

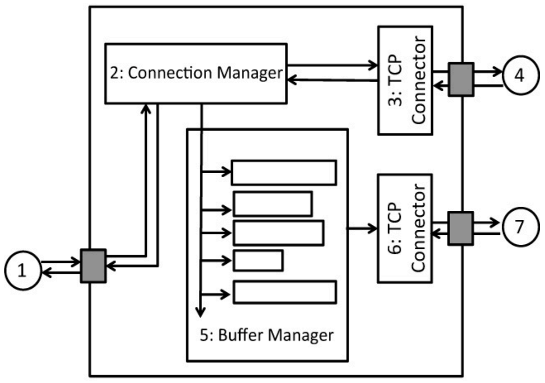

Figure 2: Description of the Network Duplicator

The production and test-container may execute at varying speeds which will result in them being slightly out of sync. Additionally we need to accept responses from both servers and drop all the traffic coming from the test-container, while still mantaining an active connection with the client. Hence a layer 2 level network solution is not possible as some context of the address and state are required

We have implemented our duplicator in two modes: (1) at TCP level, (2) at application level. The TCP level duplicator is configured with the client facing ip address (hence it becomes a a proxy), and essentially works as a socket reader/writer which reads incoming TCP streams and writes these streams to two different socket connections for the production and test containers.

The workflow of each component is as follows: Traffic from the client (Node 1 in figure 2) is forwarded to the Connection Manager(Node 2 in figure 2). The connection manager essentially is a socket reader which copies, parses the incoming traffic. Based on the type of TCP request, a new connection is created or data is forwarded/received to/from the TCP Connector(Node 3, figure 2) which in turn creates a connection to actual production server. In this way the connection manager and TCP connector follow the TCP state machine hence mantaining network packet sanity while forwarding traffic to the production container. Simultaneously, the connection manager creates an internal copy of incoming traffic, and parses and sends it to the Buffer Manager (Node 5, figure 2). In a naive scenario the connection could be simply forwarded to the test-container, and the traffic would be managed by itself. However, it is likely that the rate of traffic consumption by the test-container is less than the production container. This gives us several startegies to design the duplication of traffic to the test container:

1. **Synchronized**

   A naive startegy is to send TCP requests to the production node, and then send it to the request node

2. **Asynchronous**

   Launch two threads on accepting each TCP request. For each session of TCP requests, two threads manage sending and receiving to the production and test-container

3. **Synchronized Partial Order Multi-Threaded Queue**

Launch two threads, track slowdown of the duplication thread.

4. **Multi-Duplication**

   Launch multiple duplication threads

Since the speed of input from the client is not in sync production-container, we need to buffer incoming traffic and relay it to the the TCP Connector(Node 6, figure 2) as soon as the test-container is ready for new traffic. Since parallel connections can be initiated by the client on the same TCP port, the BufferManager creates multiple buffers for each connection, and initiates new connections by following the same causal flow of the packets received from the client. Unlike record-replay systems *Parikshan* does not claim to have strong consistency requirements, and does not need to exactly follow the production container as the goal is not reproduce all non-determinism in the production environment, but instead capture input non-determinism, and complete system state from a given point of time. We discuss consistency requirements further in section 7.3

4.3.1 *Time Delay and Buffer Management*

Incoming traffic may potentially have a cumulative effect which will eventually lead to a buffer overflow in the BufferManager, hence leading to packet drops. This behavior is similar to packet dropping in classical TCP buffers, which rely on retransmission of incoming packets from the client. However in our case if packets are dropped the client cannot retransmit them as it not in sync with the test container. Hence in some cases *Parikshan* analysis, has to be restricted to a time-window dependent on the load of incoming traffic and the slowdown experienced by the test-container.

4.4 Network State Model

Network communication in most applications consists of two core types of protocols: UDP & TCP. The UDP(User Datagram Protocol) allows the applications to send messages(referred to as datagrams) to other hosts in the network without prior communications to set up any transmission channels. UDP uses a simple communication mechanism while minimizing protocls. It has no handshaking dialogues or acknowledgement of package delivery. It is broadly used for network traffic where speed is much more important than reliability (viz. network streaming applications like video etc.) On the other hand TCP(Transmission Control Protocol) is a reliable error checked delivery stream. It involves initially establishing the connection, and allowing for packet re-delivery or re-ordering to allow for reliable and dependable connection. While TCP is slower than UDP it is preferred for most normal connections between clients and server applications.

Since the UDP protocol has no error management mechanism, it automatically follows that machine state in a UDP connection is not important. Hence in our design the duplicator can easily flood packets to the cloned UDP server by simply sending packets to the targeted host and port. Our solution for this is

5. TRIGGERING AND INSERTING ANALYSIS

Once we have forked off a clone, we are now ready to do some deeper analysis. We divide such analysis in two parts based on the time window required for analysis: (1).Statistical

5.1 Statistical Analysis

Analysis which need a long time window to record, and run the status across multiple requests are considered as long running analysis. Such analysis can be considered to be similar to monitoring of live applications, and are usually statistical in nature. Typically tools such as PIN [5], Valgrind [6], Dyninst [4], can do deep analysis without modifying the logic of the application. However, they impose a heavy penalty in terms of performance. Such tools can be easily used in *Parikshan*, without effecting system performance. However, there are a few challanges with such statistics which need a longer window to run.

5.2 Unit Tests

6. IMPLEMENTATION

Parikshan has been implemented in a small cluster environment, with physical hosts running KVM based virtual machines. Each VM is considered as a host-os for our implementation test bed. User-Space Container virtualization is done using OpenVZ[1], in Centos 6.4 kernels. Each container layout is managed using PLOOP[**?**] devices to enable faster and easier migration.

7. CHALLENGES

7.1 Non-Determinism

While the test container is a clone of production container, and they receive the same input simultaneously. They still suffer from aspects of non-determinism. Non-Determinism, can be triggered by multi-process servers, caching, or in rare circumstances it can happen because of non-determinism in the order of processing of input requests. While the change in system state between the production and test containers, may not be too important initially, we believe that the cumulative effect of non-determinism may change the

7.2 Slowdown

7.3 Consistency Requirements

8. NETWORK ISSUES

There are several problems that can effect the execution of sandbox testing.

- **Stateful Connections**
- **Time Lag**

9. IMPLEMENTATION

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10. EVALUATION

10.1 CaseStudies

10.2 Performance

- **Hypothesis 1: The test container faithfully represents the execution and state of the production container**
- **Hypothesis 2: The overhead of running a test-container in parallel does not have a significant effect on the performance of the production container**
- **Hypothesis 3: Cloning cost does not adversly effect the performance of target application**

11. CONCLUSION

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