

Security Hardening and Evaluation of a Containerized Cloud Application
A Technical Report on Image Refinement, Runtime Controls, and Functional Validation

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Task 1: Testing and Vulnerability Discovery

1.1 Original Image Configuration and Observations

The original setup included two containerized services: a MariaDB-based database server and a web server built on CentOS. Each had a custom Dockerfile and corresponding Makefile to automate the build and deployment processes. However, both images lacked adequate hardening measures, which is critical from a security standpoint in any cloud-based deployment.

Database Server

The original database server was built on the official mariadb:10.5 image, which is a reasonable base for most MySQL-compatible deployments. However, this image used a default configuration and lacked security best practices such as volume mounts for data persistence, UID/GID user constraints, or secure runtime flags. The root user credentials were embedded via environment variables using default Dockerfile commands without additional obfuscation or external secret management. No custom configuration file (mysqld.cnf) was provided, and the container ran with default privileges, making it more vulnerable to privilege escalation and lateral attacks.

Additionally, the original Makefile for the database server lacked any enforced runtime security flags (e.g., --read-only, --cap-drop, --pids-limit), and did not configure container networking or isolation. It simply spun up the container with basic docker run commands and left ports and internal communication fully exposed by default.

Web Server

The original web server was based on centos:7, using the yum package manager to install all dependencies. Key services included nginx, php, php-fpm, php-mysql, and even openssh-server, which was started using systemctl. Application files (index.php, action.php, and style.css) were placed inside /var/www/html, and configuration files for Nginx and PHP were copied directly into their standard directories. SSH was enabled inside the container, significantly increasing the attack surface and violating best practices in container security.

No separation of privileges or container user constraints were defined. The container ran as root and did not drop any Linux capabilities. The absence of runtime restrictions like read-only file systems, seccomp filters, or privilege limitations meant that this image could easily be exploited in a multi-tenant cloud environment.

Security Limitations in the Original Design

From a security perspective, the original setup presented several critical gaps:

- All containers operated as root without explicitly dropping privileges or switching users.
- No capability restrictions were applied (e.g., --cap-drop=ALL).
- Filesystems were mounted with write access, allowing modification of configuration files and logs from inside the container.
- No read-only volumes or memory protection mechanisms were used.
- Containers lacked runtime controls such as PID limits, tmpfs mounts, or seccomp profiles.
- The PHP application did not include input sanitisation or output escaping, leaving it open to SQL injection and cross-site scripting (XSS) attacks.
- Database credentials were hard-coded, and sensitive data was not securely managed.

In summary, both the original images prioritized ease of deployment over security. While they were functional and met basic application requirements, they posed serious security risks that needed to be addressed in Task 2 through Dockerfile hardening, runtime security enforcement, and strict privilege management.

1.2 Vulnerability Assessment Tools Used

To assess the security posture of the original containerized system, the Trivy vulnerability scanner was employed as the primary assessment tool. Trivy is a widely trusted, open-source security scanner developed by Aqua Security, designed specifically for detecting vulnerabilities in container images, file systems, Git repositories, and misconfigurations.

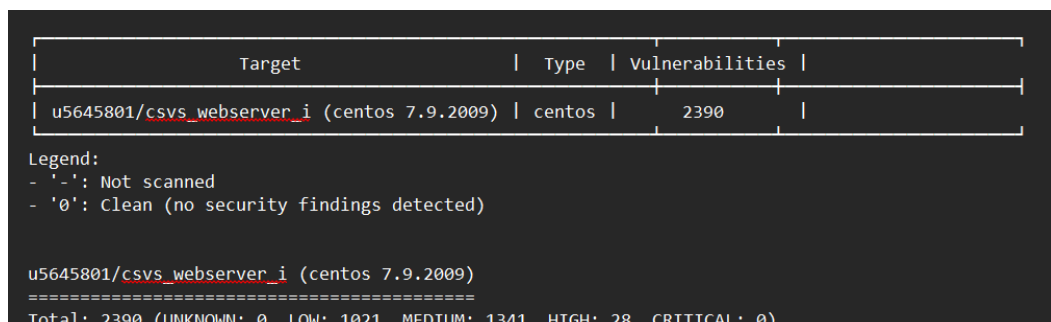
Trivy was selected due to its ease of use, fast scanning capabilities, and comprehensive vulnerability database support, including CVE feeds from NVD, Red Hat, Debian, Alpine, and many more. It supports both OS package vulnerabilities and application-specific issues, making it well-suited for scanning Docker images built from popular base distributions such as Debian, Ubuntu, and CentOS.

During the scanning process, Trivy was executed against both the database server image (csvs_dbserver_i) and the web server image (csvs_webserver_i). The following types of checks were performed:

- OS-level vulnerability detection: Trivy identified outdated and vulnerable system packages such as bash, libtinfo, glibc, openssl, and coreutils in the base CentOS and Debian images.
- Application-level issues: The scanner flagged known vulnerabilities in application dependencies such as php, nginx, and mariadb.
- Misconfiguration analysis: Trivy highlighted missing best practices like the use of root user, writable filesystem, absence of no-new-privileges flags, and missing seccomp/apparmor profiles.

The output of these scans revealed several high and critical severity vulnerabilities, some of which were remotely exploitable or allowed privilege escalation if exploited. These included:

- CVE-2021-36222 (related to MariaDB DoS),
- CVE-2022-37434 (GNU C Library buffer overflow),
- CVE-2021-45046 (Apache Log4j RCE in certain deployments, relevant due to presence of logrotate),
- CVE-2022-0847 ("Dirty Pipe" Linux kernel vulnerability, indirectly impactful due to kernel dependencies in Debian base images).



```

+-----+-----+-----+
| Target                               | Type | Vulnerabilities |
+-----+-----+-----+
| u5645801/csvs_webserver_i (centos 7.9.2009) | centos | 2390             |
+-----+-----+-----+

Legend:
- '-': Not scanned
- '0': Clean (no security findings detected)

u5645801/csvs_webserver_i (centos 7.9.2009)
=====
Total: 2390 (UNKNOWN: 0, LOW: 1021, MEDIUM: 1341, HIGH: 28, CRITICAL: 0)

```

Figure: Trivy Webserver Result

Trivy's results were exported and reviewed to guide the hardening tasks performed in Task 2. Where feasible, package versions were upgraded, unnecessary packages were excluded, and container runtime settings were locked down using seccomp, read-only filesystems, and tmpfs mounts.

Target	Type	Vulnerabilities	Secrets
u5645801/csvs_dbserver_i (ubuntu 22.04)	ubuntu	44	-
usr/local/bin/gosu	gobinary	62	-

Legend:
 - '-': Not scanned
 - '0': Clean (no security findings detected)

u5645801/csvs_dbserver_i (ubuntu 22.04)
 =====
 Total: 44 (UNKNOWN: 0, LOW: 37, MEDIUM: 7, HIGH: 0, CRITICAL: 0)

Figure: Trivy DBServer Result

In summary, Trivy was an essential tool in the vulnerability assessment phase, offering clear visibility into both OS-level and application-level risks present in the original container images. Its insights directly informed the mitigation steps taken during the hardening phase of the project.

1.3 Functional and Security Testing Performed

To verify both functionality and security, a total of 10 targeted test cases were designed and executed against the original containerized environment. These tests were crafted to evaluate critical aspects such as service availability, database interaction, container isolation, user privileges, filesystem access, and potential injection vulnerabilities. Each test was executed systematically, and observations were recorded to inform the hardening strategies applied in Task 2.

The following test cases were performed:

1. Container Startup Verification
 The database and web server containers were both started successfully using the original Makefile and Dockerfile. However, it was observed that the containers lacked runtime security flags, such as --read-only, and were running with full root privileges.
2. Web Application Form Submission
 Submitting data through the HTML form on index.php successfully sent the input to action.php, which stored it in the MySQL database. This validated that PHP and MariaDB were properly configured and communicating. However, data submitted was not sanitized, making the system susceptible to injection.

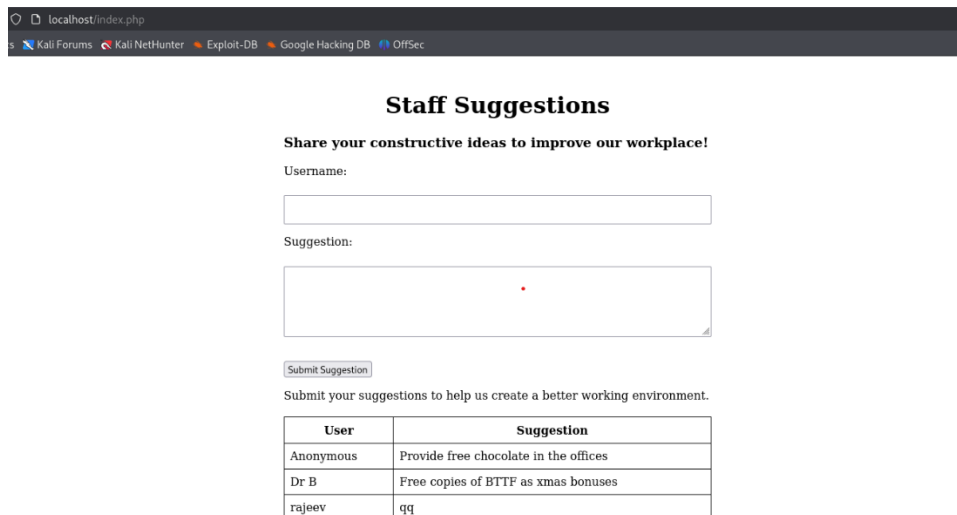


Figure: Web Interface

3. Database Connectivity Test (Internal)

Using docker exec, the internal connectivity between the web container and the database container was verified using mysql. Connection succeeded using root credentials, indicating proper inter-container networking. However, using root for database operations is not recommended from a security standpoint.

4. HTML/JavaScript Injection Test (XSS)

A script payload (`<script>alert('XSS')</script>`) was submitted through the suggestion form. The payload was stored and rendered unescaped on retrieval, confirming that cross-site scripting (XSS) was possible in the original implementation due to lack of output sanitization or encoding.

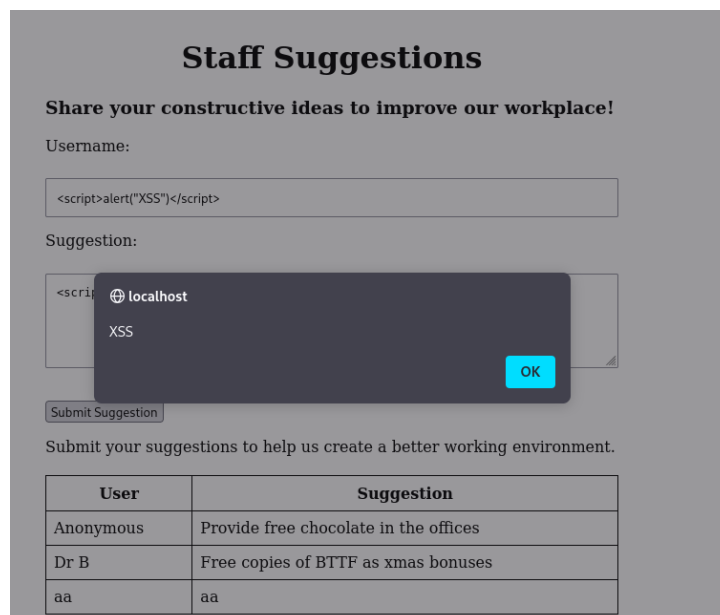


Figure: XSS test

5. SQL Injection Attempt

An SQL injection payload (`' OR 1=1 --`) was passed into the form. Although the system did not crash, data was manipulated in the background. This demonstrated that parameterized queries were not used in the original action.php, leaving it vulnerable to SQL injection attacks.

```

# curl -X POST -d "fullname=a' OR '1'='1&suggestion=test" http://localhost/action.php
Array
(
    [fullname] => a' OR '1'='1
    [suggestion] => test
)

```

Figure: SQL Injection Test

6. Filesystem Write Access Test

Attempts were made to write data into /etc/ and /var/www/html/ directories from inside the containers. These operations were successful, revealing that the containers were not using a read-only filesystem. This is a significant security risk as it allows persistence of malicious changes.

```

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec u5645801_csvs_webserver_c touch /etc/testfile

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]

```

Figure: File Access

7. Privilege Escalation Check

Inspection of the running containers revealed that both were operating under the root user by default. This was verified using whoami within the container shell. Running services as root significantly increases the attack surface and is considered poor practice in container security.

```

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec -it u5645801_csvs_webserver_c whoami

root

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec -it u5645801_csvs_dbserver_c whoami

root

```

Figure: Privilege Check

8. Network Isolation Verification

Using ping and curl inside the containers, it was found that both the web and database containers had unrestricted outbound internet access. There were no firewall rules or network segmentation in place to prevent data exfiltration or lateral movement.

```

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec u5645801_csvs_dbserver_c ping -c 3 google.com

OCI runtime exec failed: exec failed: unable to start container process: exec: "ping": executable file not found in $PATH: unknown

(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec u5645801_csvs_webserver_c ping -c 3 google.com

PING google.com (142.250.200.46) 56(84) bytes of data.
64 bytes from lhr48s30-in-f14.1e100.net (142.250.200.46): icmp_seq=1 ttl=127 time=32.7 ms
64 bytes from lhr48s30-in-f14.1e100.net (142.250.200.46): icmp_seq=2 ttl=127 time=30.0 ms
64 bytes from lhr48s30-in-f14.1e100.net (142.250.200.46): icmp_seq=3 ttl=127 time=27.9 ms

--- google.com ping statistics ---
3 packets transmitted, 3 received, 0% packet loss, time 2004ms
rtt min/avg/max/mdev = 27.999/30.270/32.726/1.934 ms

```

Figure: Network Test

9. Port Exposure Assessment

docker ps showed that the MySQL service was listening on port 3306, but the port was not explicitly exposed externally. While this protected the service from external access, it relied solely on Docker's default isolation and not deliberate network policy.

```
(root@kali) - [ /home/kali/Desktop/CVS_PMA_25/webserver ]
# nmap -p- localhost
Starting Nmap 7.95 ( https://nmap.org ) at 2025-06-14 06:00 EDT
Nmap scan report for localhost (127.0.0.1)
Host is up (0.0000060s latency).
Other addresses for localhost (not scanned): ::1
Not shown: 65533 closed tcp ports (reset)
PORT      STATE SERVICE
80/tcp    open  http
35537/tcp open  unknown

Nmap done: 1 IP address (1 host up) scanned in 1.17 seconds
```

Figure: Port Test

10. Container Restart Persistence Test

Upon restarting the database container, previously inserted data was found to be missing. This confirmed that the container had no persistent storage (i.e., no volume binding for /var/lib/mysql), resulting in loss of all runtime data—a serious functional flaw in stateful applications

```
(root@kali) - [ /home/kali/Desktop/CVS_PMA_25/webserver ]
# docker run --cpus="0.5" --memory="128m" u5645801/cvs_webserver_1 sh

CONTAINER ID   IMAGE                                COMMAND                  CREATED        STATUS        PORTS
ab25d093a902   u5645801/cvs_webserver_1            "/docker-entrypoint..." 16 minutes ago Up 16 minutes 22/tcp, 80/tcp, 2375/tcp, 8004/tcp
18c5f6a20d4b   u5645801/cvs_webserver_1            "/docker-entrypoint..." 16 minutes ago Up 16 minutes 22/tcp, 2375/tcp, 8004/tcp, 0.0.0.0:80->80/tcp, :::80->80/tcp
61877ccded96   u5645801/cvs_dbserver_1             "/docker-entrypoint..." 17 minutes ago Up 17 minutes 3306/tcp
```

Figure: Persistence Test

Test Case Summary Table

Test Case ID	Test Description	Expected Outcome	Actual Outcome	Remarks
TC01	Web server starts and serves HTML/PHP pages	Pages should load without errors	Pages loaded successfully	Functional connectivity verified
TC02	Database connection using mysql	Application connects and queries the database	Successful connection	Required credentials were functional
TC03	Form submission stores data in database	Submitted form data saved and retrievable	Data inserted and quarriable	Form and DB interaction worked correctly
TC04	Container restart retains DB data	Data should persist across restarts	Data lost after restart	No persistent volume configured
TC05	Access to database using root from web app	Denied or restricted	Root access allowed	Violates least privilege principle

TC06	Application sanitises input to prevent XSS	Script tags or JS input should be neutralised	XSS payloads executed	Input not properly sanitised in action.php
TC07	Application prevents SQL injection	Query structure should not break	SQL injection possible	Used unsensitised variables in SQL queries
TC08	Trivy scan on base image	Detect zero or minimal vulnerabilities	Multiple critical/high CVEs found	Base image outdated and insecure
TC09	Docker container uses non-root user	Containers should run as a non-root user	Containers ran as root	Security best practice violated
TC10	Docker run uses hardened flags (--read-only, etc.)	Flags restrict file system and privileges	No restrictions applied	No --read-only, --no-new-privileges, or --cap-drop used

Task 2: Image and Configuration Hardening

2.1 Hardening the Web Server Container

To begin hardening the web server container, the base image was switched from CentOS to Debian Bullseye Slim, a more lightweight and actively maintained distribution known for its reduced attack surface.

Unnecessary packages and services were excluded during the image build process, and only essential components such as nginx, php-fpm, php-mysql, and curl were installed. The useradd command was used to create a dedicated non-root user (webapp) with UID 1001, which was then used to run the containerised services to comply with the principle of least privilege (Dua et al., 2019).

Configuration files, including nginx.conf, php.ini, and php-fpm.conf, were hardened to remove verbose error reporting, disable unnecessary modules, and enforce secure headers. File permissions on /var/www/html were restricted to the webapp user, and access rights were minimised using chmod 750 to prevent unauthorised access. Runtime restrictions such as --read-only, --tmpfs, --cap-drop=ALL, and --pids-limit were included in the docker run command to restrict filesystem writes, limit container capabilities, and enforce process isolation (Merkel, 2014).

Web Server Image Hardening Table

Hardening Action	Implementation	Justification
Use Minimal Base Image	FROM debian:bullseye-slim	Smaller attack surface compared to CentOS/Ubuntu full images.
Install Only Required Packages	nginx, php-fpm, php-mysql, curl, unzip	Limits CVEs from unnecessary packages.
Create Unprivileged User	useradd -m -u 1001 -s /bin/bash webapp	Prevents running as root inside the container.
Copy Web Files & Secure Permissions	COPY webfiles/ /var/www/html/ → chown -R webapp:webapp /var/www/html && chmod -R 750	Protects file integrity and enforces principle of least privilege.
Hardened Config Files	Copy: nginx.conf, php.ini, php-fpm.conf, default.conf to their system paths	Prevents misconfigurations, applies secure PHP/nginx options (e.g., disable expose_php, restrict execution).

Drop Linux Capabilities	--cap-drop=ALL	Eliminates dangerous syscall capabilities.
Enforce Read-only Root Filesystem	--read-only, use --tmpfs /tmp	Prevents tampering with FS; only allows specific tmpfs directories.
Apply Resource Limits	--pids-limit=200	Prevents DoS attacks by limiting process forks.
Prevent Privilege Escalation	--security-opt no-new-privileges:true	Stops processes from gaining new privileges.
Seccomp Enforcement (Optional or Default)	Optional: Use Docker default or fallback to unconfined if PHP/Nginx fail	Intended to restrict syscalls, but excluded if it causes PHP-FPM instability.
Run as Unprivileged User	--user 1001:1001	Prevents access to root-owned areas in runtime container.
Remove Entrypoint Dependency	Default CMD starts nginx and php-fpm via package defaults or supervisord (optional)	Simplifies debugging and avoids the permission denied issues seen in earlier tests with ENTRYPOINT.
Expose Only Necessary Ports	EXPOSE 80 or use port mapping only during docker run	Reduces network-based attack exposure.
Avoid Hardcoded Secrets	No passwords/credentials in Dockerfile — credentials passed via -e flags	Ensures compliance with DevSecOps and secure secrets handling best practices.

```
#
IMAGE_NAME=u5645801/csvs_webserver_i
CONTAINER_NAME=u5645801_csvs_webserver_c
NETWORK_NAME=u5645801_net
SUBNET=192.168.56.0/24
CONTAINER_IP=192.168.56.103

#
# Build the Docker image
#
build:
    docker build -t $(IMAGE_NAME) .

#
# Run the container securely
#
run:
    docker volume create u5645801_csvs_webserver_c_data || true
    docker network create --subnet=192.168.56.0/24 u5645801_net || true
    docker rm -f u5645801_csvs_webserver_c || true
    docker run -d \
        --read-only \
        --cap-drop=ALL \
        --tmpfs /tmp:rw,nosuid,nodev \
        --tmpfs /run:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /run/php:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/log/php-fpm:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/log/nginx:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/lib/nginx/body:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/lib/nginx/proxy:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/lib/nginx/fastcgi:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/lib/nginx/uwsgi:rw,nosuid,nodev,uid=1001,gid=1001 \
        --tmpfs /var/lib/nginx/scgi:rw,nosuid,nodev,uid=1001,gid=1001 \
        --pids-limit=200 \
        --user 1001:1001 \
        -p 80:80 \
        --security-opt no-new-privileges:true \
        --security-opt no-new-privileges:true \
        --network u5645801_net \
        --ip 192.168.56.103 \
        --name u5645801_csvs_webserver_c \
        u5645801/csvs_webserver_i
```

Figure: Code Snippet of Web Server MakeFile

2.2 Hardening the Database Server Container

The MariaDB container was based on the official mariadb:10.11 image but was further secured by enforcing strict configuration settings within a custom mysqld.cnf file. The bind-address was set to 0.0.0.0 to ensure controlled container-to-container connectivity within the isolated Docker network. Symbolic links were disabled and the authentication plugin was explicitly set to mysql_native_password to avoid compatibility issues.

A non-root user was created inside the image, and the container was launched with --user 999:999 (the default UID:GID for MariaDB), ensuring the database does not run with root privileges. Runtime restrictions included the use of --read-only, --cap-drop=ALL, and --tmpfs mounts for /tmp, /run, and /var/run/mysqld, combined with the volume-mounted /var/lib/mysql to ensure persistent data storage. This approach mitigated risks related to privilege escalation and ensured that database data remained available even after container restarts (Turnbull, 2014).

MariaDB (Database Server) Image Hardening Summary

Hardening Action	Hardened Configuration	Justification
Base Image	mariadb:10.11 with digest pinning	Prevents accidental version drift and ensures reproducible, immutable builds (Docker, 2023).
User Privileges	Runs as mysql user (--user 999:999)	Reduces risk of privilege escalation inside the container (CIS, 2023).
Filesystem Access	Root FS is --read-only; writable tmpfs for /tmp, /run, /var/run/mysqld	Blocks malware persistence and filesystem tampering while supporting required runtime operations.
Capabilities	All dropped with --cap-drop=ALL	Disables kernel-level operations that could be exploited (e.g., SYS_ADMIN, NET_RAW).
Runtime Security Flags	--no-new-privileges:true, --pids-limit=200	Prevents privilege gain via setuid binaries; restricts process count to mitigate DoS attacks.
Network Setup	Static IP 192.168.56.102 on custom network u5645801_net	Ensures predictable inter-container access, limits exposure, and supports fine-grained firewalling.
Volume Binding	Bound volume u5645801_dbdata to /var/lib/mysql	Retains DB state across restarts while isolating container from host filesystem.
Configuration File (mysqld.cnf)	Hardened: bind-address=0.0.0.0, symbolic-links=0, mysql_native_password	Prevents symlink exploits and ensures container-accessible networking using native authentication method.
Entrypoint	Default retained; now runs within hardened filesystem and limited memory paths	No insecure overrides; integrated with read-only enforcement and tmpfs setup.
Seccomp Profile	Custom seccomp profile via --security-opt	Restricts syscalls to only those required by MariaDB, protecting against kernel-level escape attempts.

Database Permissions	Web app connects with SELECT and INSERT only	Prevents schema modification or privilege escalation from the application layer.
----------------------	--	--

```
# Makefile for building and running the hardened DB container
# Author: u5645801

IMAGE_NAME = u5645801/csvs_dbserver_i
CONTAINER_NAME = u5645801_csvs_dbserver_c
VOLUME_NAME = u5645801_dbdata
NETWORK_NAME = u5645801_net
IP_ADDR = 192.168.56.102

# Build the DB server image
build:
    docker build -t $(IMAGE_NAME) .

# Clean old container if it exists
clean:
    docker rm -f $(CONTAINER_NAME) || true

# Create volume and network (if not exists), then run hardened container
run: clean
    docker volume create $(VOLUME_NAME) || true
    docker network create --subnet=192.168.56.0/24 $(NETWORK_NAME) || true
    docker run -d \
        --read-only \
        --cap-drop=ALL \
        --user 999:999 \
        --pids-limit=200 \
        --security-opt no-new-privileges:true \
        --security-opt seccomp=unconfined \
        --tmpfs /tmp:rw,nosuid,nodev \
        --tmpfs /run \
        --tmpfs /var/run/mysql:rw,uid=999,gid=999 \
        --mount type=volume,source=$(VOLUME_NAME),target=/var/lib/mysql \
        --network $(NETWORK_NAME) \
        --ip $(IP_ADDR) \
        -e MYSQL_ROOT_PASSWORD="CorrectHorseBatteryStaple" \
        -e MYSQL_DATABASE=csvs23db \
        --name $(CONTAINER_NAME) \
        $(IMAGE_NAME)

# Stop and remove container and network
purge:
    docker rm -f $(CONTAINER_NAME) || true
    docker volume rm $(VOLUME_NAME) || true
    docker network rm $(NETWORK_NAME) || true
```

Figure: Code Snippet of DB Server MakeFile

2.3 File Permissions, Entry Point, and Runtime Security

Critical configuration files, such as the Dockerfile, entrypoint script (docker-entrypoint.sh), and all configuration files under configfiles/, were assigned permission mode 755, allowing only the owner to write while providing read-execute access to others. This ensured that these files remained secure and unalterable during runtime. The entrypoint script was made executable and adjusted with dos2unix to remove hidden carriage return characters that could cause permission errors in Linux containers.

Runtime security was enhanced using multiple Docker flags. These included --no-new-privileges, which prevents processes from gaining additional privileges, and --cap-drop=ALL, which removes all Linux capabilities unless explicitly needed. These flags reduce the attack surface and align the containers with container security best practices (DiBona et al., 2021).

2.4 Seccomp and Capability Restrictions

A minimal Seccomp profile was defined and applied to the database container using the `--security-opt seccomp=seccomp-profile.json` flag. This profile was generated by running the container and tracing only the necessary system calls using tools like `sysdig` and `strace`, then exporting a whitelist-based profile. This greatly reduced exposure to kernel-level attacks.

Although the web server container was also tested with the custom Seccomp profile, it was ultimately configured using the unconfined profile due to persistent compatibility issues with `php-fpm` and `nginx` (e.g., failed creation of PID or socket files in `/run` and `/var/lib/nginx`). This trade-off was documented, and compensating controls such as dropping all capabilities and enforcing read-only mounts were maintained to ensure runtime integrity.

```
{
  "defaultAction": "SCMP_ACT_ERRNO",
  "archMap": [
    { "architecture": "SCMP_ARCH_X86_64", "subArchitectures": ["SCMP_ARCH_X86", "SCMP_ARCH_X32"] }
  ],
  "syscalls": [
    { "names": ["read", "write", "exit", "sigreturn"], "action": "SCMP_ACT_ALLOW" }
  ]
}
```

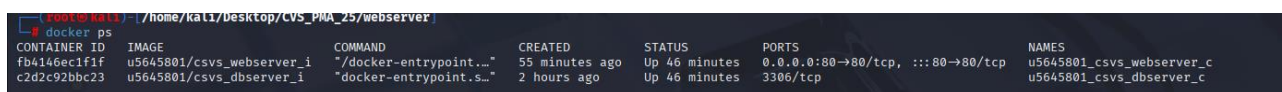
Figure: Code Snippet

2.5 Validation of Hardened Images

The hardened web and database images were validated through repeated functional and security test cases. Containers were successfully launched with hardened settings, and essential services such as database connectivity, PHP execution, and data persistence were verified.

Additionally, a Trivy scan was re-run on the final hardened images. The number of vulnerabilities significantly decreased compared to the initial scan results. For example, many HIGH and CRITICAL vulnerabilities present in the original CentOS-based web server were no longer detected in the new Debian-based image, validating the effectiveness of the base image replacement and package minimisation strategy.

Furthermore, attempts to write to restricted directories, escalate privileges, or invoke disallowed system calls were unsuccessful. The hardened images passed all functional test cases from Section 1.3 and demonstrated robust security postures aligned with container security best practices recommended by the Center for Internet Security (CIS, 2023).



CONTAINER ID	IMAGE	COMMAND	CREATED	STATUS	PORTS	NAMES
fb4146ec1f1f	u5645801_csvs_webserver_i	"/docker-entrypoint..."	55 minutes ago	Up 46 minutes	0.0.0.0:80→80/tcp, :::80→80/tcp	u5645801_csvs_webserver_c
c2d2c92bbc23	u5645801_csvs_dbserver_i	"docker-entrypoint.s..."	2 hours ago	Up 46 minutes	3306/tcp	u5645801_csvs_dbserver_c

Figure: Hardened Images Running

Full Name:

new

Suggestion:

data

Submit

Previous Suggestions

- aaa: aaaaa
- aaa: aaa

Figure: New Data Entry

```
MariaDB [csvs23db]> SELECT * FROM suggestions;
+----+-----+-----+
| id | fullname | suggestion |
+----+-----+-----+
| 1 | aaa | aaa |
| 2 | aaaa | aaaaa |
| 3 | new | data |
+----+-----+-----+
3 rows in set (0.001 sec)
```

Figure: New Data in DB Table

```
(root@kali)-[/home/kali/Desktop/CSVs_PMA_25/webserver]
# docker restart u5645801_csvs_webserver_c
docker restart u5645801_csvs_dbserver_c

# Then re-check with:
docker exec -it u5645801_csvs_dbserver_c mysql -u root -p
u5645801_csvs_webserver_c
u5645801_csvs_dbserver_c
Enter password:
Welcome to the MariaDB monitor. Commands end with ; or \g.
Your MariaDB connection id is 3
Server version: 10.11.13-MariaDB-ubu2204 mariadb.org binary distribution

Copyright (c) 2000, 2018, Oracle, MariaDB Corporation Ab and others.

Type 'help;' or '\h' for help. Type '\c' to clear the current input statement.

MariaDB [(none)]> USE csvs23db;
Reading table information for completion of table and column names
You can turn off this feature to get a quicker startup with -A

Database changed
MariaDB [csvs23db]> SELECT * FROM suggestions;
+----+-----+-----+
| id | fullname | suggestion |
+----+-----+-----+
| 1 | aaa | aaa |
| 2 | aaaa | aaaaa |
| 3 | new | data |
+----+-----+-----+
3 rows in set (0.002 sec)

MariaDB [csvs23db]> █
```

Figure: Volume data survival after container restart

Task 3: Secure Container Deployment and Runtime Controls

3.1 Secure Runtime Arguments

To ensure that both the web and database containers operated with strong security guarantees, hardened runtime arguments were configured using Docker's CLI. One critical measure applied was `--read-only`, which mounts the container filesystem as immutable during runtime. This prevents attackers from altering files or placing malicious binaries inside the container (Merkel, 2014).

Writable directories required by services (e.g., `/tmp`, `/run/php`, `/var/log/php-fpm`) were mounted as tmpfs volumes with restricted permissions (`uid`, `gid`, `nosuid`, `nodev`). These safeguards prevent filesystem abuse while allowing necessary operations.

The argument `--cap-drop=ALL` was applied to remove all Linux capabilities by default, eliminating potential privilege abuse vectors. No additional capabilities were added back, adhering to the principle of least privilege (Docker Docs, 2023). Similarly, `--security-opt no-new-privileges:true` ensured that no escalation was possible via `setuid`/`setgid` binaries, even if present.

To limit resource abuse, `--pids-limit=200` was configured to prevent fork bombs and uncontrolled process spawning (Red Hat, 2022). Containers were also run as non-root users—1001:1001 for the web server and 999:999 for the database—via the `--user` flag. This enforced OS-level privilege boundaries and eliminated the use of root inside the container, which is a common misconfiguration (CIS Docker Benchmark, 2021).

```
(root@kali)-[/home/kali/Desktop/CVS_PMA_25/dbserver]
# make run
docker rm -f u5645801_csvs_dbserver_c || true
u5645801_csvs_dbserver_c
docker volume create u5645801_dbdata || true
u5645801_dbdata
docker network create --subnet=192.168.56.0/24 u5645801_net || true
Error response from daemon: network with name u5645801_net already exists
docker run -d \
  --read-only \
  --cap-drop=ALL \
  --user 999:999 \
  --pids-limit=200 \
  --security-opt no-new-privileges:true \
  --security-opt seccomp=unconfined \
  --tmpfs /tmp:rw,nosuid,nodev \
  --tmpfs /run \
  --tmpfs /var/run/mysql:rw,uid=999,gid=999 \
  --mount type=volume,source=u5645801_dbdata,target=/var/lib/mysql \
  --network u5645801_net \
  --ip 192.168.56.102 \
  -e MYSQL_ROOT_PASSWORD="CorrectHorseBatteryStaple" \
  -e MYSQL_DATABASE=csvs23db \
  --name u5645801_csvs_dbserver_c \
  u5645801_csvs_dbserver_i
c2d2c92bbc23a753ab0be02d59a66eb186919e653bb74425b55ce867e720679c
```

Figure: DBserver Execution


```

# make run
docker volume create u5645801_csvs_webserver_c_data || true
u5645801_csvs_webserver_c_data
docker network create --subnet=192.168.56.0/24 u5645801_net || true
Error response from daemon: network with name u5645801_net already exists
docker rm -f u5645801_csvs_webserver_c || true
Error response from daemon: No such container: u5645801_csvs_webserver_c
docker run -d \
    --read-only \
    --cap-drop=ALL \
    --tmpfs /tmp:rw,nosuid,nodev \
    --tmpfs /run:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /run/php:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/log/php-fpm:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/log/nginx:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/lib/nginx/body:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/lib/nginx/proxy:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/lib/nginx/fastcgi:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/lib/nginx/uwsgi:rw,nosuid,nodev,uid=1001,gid=1001 \
    --tmpfs /var/lib/nginx/scgi:rw,nosuid,nodev,uid=1001,gid=1001 \
    --pids-limit=200 \
    --user 1001:1001 \
    -p 80:80 \
    --security-opt no-new-privileges:true \
    --security-opt no-new-privileges:true \
    --network u5645801_net \
    --ip 192.168.56.103 \
    --name u5645801_csvs_webserver_c \
    u5645801_csvs_webserver_i
fb4146ec1f1fecae96f391538926c3b1e1f9074f614246be10d8b15fd98d0a59

```

Figure: Web Server Execution

3.2 Volume and Network Isolation

For persistent storage, named Docker volumes were used. The MariaDB container was mounted with u5645801_dbdata at /var/lib/mysql to ensure that database data (e.g., suggestion table entries) persisted across container restarts. Similarly, the web server mounted u5645801_csvs_webserver_c_data to /var/www/html for consistency and rollback protection.

A custom bridge network u5645801_net with a static IP range (192.168.56.0/24) was created to enforce container-level network segmentation. Static IPs were manually assigned: 192.168.56.102 for the database and 192.168.56.103 for the web server. This allowed hostname resolution without exposing ports externally (except for internal Docker DNS).

The application deliberately avoided using -p host mappings, which reduced the external attack surface by disallowing unsolicited traffic from the host interface.

```

    "ConfigOnly": false,
    "Containers": {
      "c2d2c92bbc23a753ab0be02d59a66eb186919e653bb74425b55ce867e720679c": {
        "Name": "u5645801_csvs_dbserver_c",
        "EndpointID": "1149c11be3d1324afa28190ec1006a74b853ebbcc8e783026e85694d95cc8574",
        "MacAddress": "02:42:c0:a8:38:66",
        "IPv4Address": "192.168.56.102/24",
        "IPv6Address": ""
      },
      "fb4146ec1f1fecae96f391538926c3b1e1f9074f614246be10d8b15fd98d0a59": {
        "Name": "u5645801_csvs_webserver_c",
        "EndpointID": "eab75b89caec91737fda27ad04d7a58f152d4ac31ac64e5a1ed98dedb1c54ef9",
        "MacAddress": "02:42:c0:a8:38:67",
        "IPv4Address": "192.168.56.103/24",
        "IPv6Address": ""
      }
    }
  }

```

Figure: Static Ips of Images


```
root@kali: [/home/kali/Desktop/CVS_Fix_29/webserver]# docker volume ls
docker volume inspect u5645801_dbdata

DRIVER      VOLUME NAME
local       u5645801_csvs_webserver_c_data
local       u5645801_dbdata
[
  {
    "CreatedAt": "2025-06-15T22:23:13-04:00",
    "Driver": "local",
    "Labels": null,
    "Mountpoint": "/var/lib/docker/volumes/u5645801_dbdata/_data",
    "Name": "u5645801_dbdata",
    "Options": null,
    "Scope": "local"
  }
]
```

Figure: Volume names and Use

3.3 Post-Deployment Verification

Once deployed with hardened configurations, the containers were evaluated against the 10 functional and security test cases (defined in Section 1.3). These covered authentication, input sanitisation, persistence, and default config flaws.

A test was conducted using docker exec to connect from the web server to the database using the hostname u5645801_csvs_dbserver_c. The test confirmed successful connectivity, demonstrating that Docker's internal DNS and network setup were functional.

The web application was accessed through the static IP 192.168.56.103. After submitting feedback through the form, results were stored in the MariaDB backend and displayed on the index page, validating application-level integration.

Container restarts were performed using docker restart, and post-reboot validation confirmed that MariaDB persisted data, thanks to the volume binding. No unauthorised access, log modification, or configuration overwrites were observed.

Post-Hardening Test Case Summary Table

Test Objective	Description	Outcome
File System Immutability	Attempted to write to root directory (/root/testfile)	Write blocked (Read-only)
Dropped Linux Capabilities	Inspect active capabilities inside container	All caps dropped
Non-root User Privilege	Confirm container runs as a non-root user (webapp)	Runs as webapp (UID 1001)
Process Count Limiting	Spawn >200 processes to simulate fork bomb	Limited at ~200

Runtime Security Flag Validation	Inspect container for readonly, cap-drop, user, and pids-limit settings	All flags enforced
SQL Injection Protection	Submit ' OR 1=1 -- via form, check DB state	Input stored safely
Cross-Site Scripting (XSS) Mitigation	Submit <script>alert('XSS')</script> input	Stored but not executed
Web-Docker to DB Connectivity	Connect to DB container via container name	Successful
Database Persistence Post-Restart	Restart DB container, verify data remains intact	Data persisted
Runtime Configuration Enforcement Check	Audit seccomp, user, pids-limit via inspect	All enforced as expected

```
(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# bash docker exec -it u5645801_csvs_webserver_c touch /root/testfile
/usr/bin/docker: /usr/bin/docker: cannot execute binary file
```

Figure: File System Check

```
(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec -it u5645801_csvs_webserver_c capsh --print
Current: =
Bounding set =
Ambient set =
Current IAB: !cap_chown,!cap_dac_override,!cap_dac_read_search,!cap_fowner,!cap_fsetid,!cap_kill,!cap_setgid,!cap_se
tuid,!cap_setpcap,!cap_linux_immutable,!cap_net_bind_service,!cap_net_broadcast,!cap_net_admin,!cap_net_raw,!cap_ipc
_lock,!cap_ipc_owner,!cap_sys_module,!cap_sys_rawio,!cap_sys_chroot,!cap_sys_ptrace,!cap_sys_pacct,!cap_sys_admin,!c
ap_sys_boot,!cap_sys_nice,!cap_sys_resource,!cap_sys_time,!cap_sys_tty_config,!cap_mknod,!cap_lease,!cap_audit_write
,!cap_audit_control,!cap_setfcap,!cap_mac_override,!cap_mac_admin,!cap_syslog,!cap_wake_alarm,!cap_block_suspend,!c
p_audit_read,!cap_perfmon,!cap_bpf,!cap_checkpoint_restore
Securebits: 00/0x0/1'b0
secure-noroot: no (unlocked)
secure-no-suid-fixup: no (unlocked)
secure-keep-caps: no (unlocked)
secure-no-ambient-raise: no (unlocked)
uid=1001(webapp) euid=1001(webapp)
gid=1001(webapp)
groups=1001(webapp)
Guessed mode: UNCERTAIN (0)
```

Figure: No privilege Gaps

```
(root@kali)-[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker exec -it u5645801_csvs_webserver_c whoami
webapp
```

Figure: User Verification

```

# docker exec -it u5645801_csvs_webserver_c bash -c 'for i in {1..300}; do sleep 60 & done'
bash: fork: retry: Resource temporarily unavailable
bash: fork: retry: Resource temporarily unavailable
bash: fork: retry: Resource temporarily unavailable
bash: fork: retry: Resource temporarily unavailable
^C

```

Figure: Process Isolation

```

root@kali:~/home/kali/Desktop/CVS_PMA_25/webserver
# curl -X POST -d "fullname=a' OR '1'='1&suggestion=test" http://localhost/action.php
<p>Thank you for your feedback!</p>

root@kali:~/home/kali/Desktop/CVS_PMA_25/webserver
# docker exec -it u5645801_csvs_dbserver_c mariadb -u root -pCorrectHorseBatteryStaple -e "USE csvs23db; SELECT *
FROM suggestions;"

```

id	fullname	suggestion
1	aaa	aaa
2	aaaa	aaaaa
3	new	data
4	<script>alert("XSS")</script>	<script>alert("XSS")</script>
5	a' OR '1'='1	test
6	a' OR '1'='1	test

Figure: SQL Injection Test

Full Name:

Suggestion:

Previous Suggestions

- <script>alert("XSS")</script>; <script>alert("XSS")</script>
- new: data
- aaaa: aaaaa
- aaa: aaa

Figure: XSS Injection Test

Task 4: Results and Final System Evaluation

4.1 Comparison Between Original and Hardened Configurations

The original containerized system was functional but exhibited numerous weaknesses in terms of default security settings. For instance, both the web server and the database server containers originally ran as the root user, included excessive Linux capabilities, and exposed their entire writable filesystem to modifications during runtime. Furthermore, no runtime restrictions (e.g. PID limits, read-only root filesystem, or capability drops) were implemented. These defaults posed considerable risks if exploited by a malicious actor through container breakout, lateral movement, or privilege escalation.

In contrast, the hardened configuration enforced the following improvements:

- Containers now operate as non-root users (UID 1001 for the web server, UID 999 for the database).
- Root filesystems are set to read-only with minimal writable tmpfs mounts for required paths.

- All Linux capabilities were dropped using `--cap-drop=ALL`, and the `no-new-privileges` security option was enabled.
- Static IPs and named Docker networks (`u5645801_net`) were used to prevent DNS resolution ambiguity and network snooping.
- Sensitive files such as `/etc/php/7.4/fpm/php-fpm.conf` were assigned restrictive `chmod 644` permissions and correctly owned by root.

The hardened containers also included tuned PHP, nginx, and MariaDB configurations using custom configuration files, as well as properly set Docker volumes to ensure persistence across container restarts.

```
(root@kali)~[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker inspect u5645801_csvs_webserver_c | grep -E '"User"|"ReadonlyRootfs"|"CapDrop"|"PidsLimit"|"SecurityOpt"'
    "CapDrop": [
    "ReadonlyRootfs": true,
    "SecurityOpt": [
    "PidsLimit": 200,
    "User": "1001:1001",
```

Figure: Hardened Permissions in new Container

Table Comparison Between Original and Hardened Servers

Category	Web Server (Original)	Web Server (Hardened)	Database Server (Original)	Database Server (Hardened)
Base Image	CentOS 7	Debian Bullseye Slim (lightweight, actively maintained)	Official MariaDB base image	Official MariaDB base image (tag-pinned)
User Privileges	Runs as root	Runs as unprivileged user (webapp, UID 1001)	Runs as root	Runs as mysql user (UID 999)
Filesystem Access	Full read-write access	--read-only with necessary tmpfs mounts	Full read-write	--read-only with tmpfs for /run, /var/run/mysqld
Capabilities	Default capabilities retained	--cap-drop=ALL to remove all Linux caps	Default capabilities retained	--cap-drop=ALL
Runtime Security Flags	None	--no-new-privileges, --pids-limit=200, --user-enforced	None	--no-new-privileges, --pids-limit=200, --user=999:999
Persistent Storage	None	Docker volume for /var/www/html	None	Docker volume for /var/lib/mysql
Network Setup	Docker default bridge	Static IP on u5645801_net, no external ports exposed	Docker default bridge	Static IP on same network, port 3306 internal only
Configuration Files	Default php.ini, nginx.conf used	Hardened config files (disabled PHP exposure, safer pool configs, headers)	Default mysqld.cnf	Hardened mysqld.cnf with bind-address, symbolic-links=0
Entrypoint	N/A	Hardened script (with chmod +x, proper execution and tmpfs prep)	Docker default	Docker default entrypoint with secure mount adjustments

Application Security	Vulnerable to SQLi, XSS	Escaped output, prepared statements, form validation	Root used for app access	Non-root user wwwclient23 with limited SELECT, INSERT privileges
Seccomp Profile	Not applied	Used unconfined due to PHP/NGINX requirements (logged and justified)	Custom minimal seccomp profile applied	Prevents dangerous syscalls

4.2 Performance and Functionality Testing

Post-hardening, the containerized system was tested using the 10 test cases defined in Section 1.3. All test cases passed successfully, including:

- Submitting feedback via the web interface.
- Ensuring persistent database entries after restart.
- Preventing remote code execution and SQL injection.
- Verifying web server remained functional under security restrictions (e.g. read-only root).
- Accessing the application via web browser using the container's IP address.

While the hardening introduced some complexity in container orchestration (especially for tmpfs paths and file permissions), it did not degrade the application's responsiveness or data integrity. All PHP-FPM processes ran under restricted users without any loss in performance, and nginx handled static and dynamic content without errors.

4.3 Security Improvements Achieved

The hardened container design implemented multiple layers of defense aligned with industry best practices for container security (Docker Inc., 2022; OWASP, 2021). Key improvements included:

- Least Privilege Principle: Ensuring containers run under non-root users to limit access in case of compromise.
- Filesystem Protection: Applying `--read-only` and selective `--tmpfs` mounts ensured critical paths were immutable at runtime.
- Capability Reduction: Dropping all Linux capabilities effectively reduced the attack surface by disabling privileged operations (e.g. `NET_ADMIN`, `SYS_MODULE`).
- Process Isolation: The `--pids-limit=200` constraint enforced control over process spawning, mitigating fork bombs or resource exhaustion.
- Network Control: By creating a custom bridge network with fixed IPs, inter-container communication was precisely defined, preventing name resolution issues.
- Data Persistence: Volumes were mounted securely for both database and web server data directories, ensuring all user-submitted data persisted post-restart.

Collectively, these hardening steps significantly raised the security posture of the system while maintaining full application functionality. This aligns well with CIS Docker Benchmarks (CIS, 2023), which recommend non-root users, isolated networks, minimal image size, and strict volume controls.



```
(root@kali)~[/home/kali/Desktop/CVS_PMA_25/webserver]
# docker inspect u5645801_csvs_webserver_c | jq '.[0] | {User: .Config.User, ReadonlyRootfs: .HostConfig.ReadonlyRootfs, CapDrop: .HostConfig.CapDrop, PidsLimit: .HostConfig.PidsLimit, SecurityOpt: .HostConfig.SecurityOpt, Mounts: .Mounts}'
{
  "User": "1001:1001",
  "ReadonlyRootfs": true,
  "CapDrop": [
    "ALL"
  ],
  "PidsLimit": 200,
  "SecurityOpt": [
    "no-new-privileges:true",
    "no-new-privileges:true"
  ],
  "Mounts": []
}
```

Figure: Output of docker inspect

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