Towards a Security Stress-Test for Cloud Configurations

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Abstract—Securing cloud configurations is an elusive task, which is left up to system administrators who have to base their decisions on "trial and error" experimentations or by observing good practices (e.g., CIS Benchmarks). We propose a knowledge, AND/OR, graphs approach to model cloud deployment security objects and vulnerabilities. In this way, we can capture relationships between configurations, permissions (e.g., CAP_SYS_ADMIN), and security profiles (e.g., AppArmor and SecComp), as first-class citizens. Such an approach allows us to suggest alternative and safer configurations, support administrators in the study of what-if scenarios, and scale the analysis to large scale deployments. We present an initial validation and illustrate the approach with three real vulnerabilities from known sources.

Index Terms—knowledge graph, AND/OR graphs, containers, security, microservices, cloud

I. INTRODUCTION

Container engines and orchestration tools, such as Docker and Kubernetes, abstract the complexity of the underlying technologies (e.g. Linux namespaces and Control Groups). This power of abstraction reduces companies' time to market, by making it easier to deploy and share applications. Yet, it also rises new security challenges. Indeed, it is hard to understand such hidden complexity in a highly dynamic environment (44% of containers are executed for less than five minutes [1]). Misconfiguration is the most prevalent vulnerability in the cloud [2], 76% containers are running as root, and 75% of containers are running with critical vulnerabilities [1] (§II).

Several tools exist for analyzing container deployments and for vulnerability scanning. Yet, as we illustrate in the related section (§III), most 'vulnerability scanners' are actually simply checkers of bills of (software materials). When actual configurations are checked (e.g. the Checkov tool) they are checked against best practices (i.e. CIS Benchmarks). Such analysis reports rules that are not met but cannot do a more sophisticated what-if analysis of what can be changed while maintaining a satisfying secure configuration.

To fill this gap, we propose to use a knowledge graphs where objects, permissions, capabilities and other security features (e.g. AppArmor for Docker) are first class citizens of the model. To this end, we build such knowledge graphs and contribute with search algorithms implemented in Python

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and Neo4J (§IV) to identify vulnerabilities and their fixes (§V). Fig. 1 shows the workflow steps of the stress-test on Docker containers, namely, (i) building the knowledge graph from configuration files, (ii) enriching the graph with known vulnerabilities, and (iii), testing and fixing the system by interacting with the user.

The idea is to construct with this methodology the equivalent of a stress-test¹ for cloud configuration. The methodology will allow administrators to explore what-if scenarios whenever a new vulnerability is discovered and better understand the trade-offs made between relaxing security requirements and functionality loss.

We present an initial validation by illustrating the proposed approach in §VI and discuss the results and future work in §VII. We present the concluding remarks in§VIII.

II. SIMPLE ATTACK SCENARIOS

To illustrate the problem faced by administrators in charge of cloud deployment, we describe two recent attack scenarios and their implications for containers. In 2019, a researcher from Google posted on Twitter a proof of concept (PoC) to escape from privileged Docker containers, by exploiting the release_agent of control groups (cgroups) [4]. Listing 1 shows a possible vulnerable configuration. This configuration adds system administrator capabilities to the default root user of Docker and tells the system to avoid a specific AppArmor Linux profile, a solution typically used to make sure applications can more easily communicate across network sockets.

Listing 1. Vulnerable execution of the container taken from [4] # On the host
docker run --rm -it --cap-add=SYS_ADMIN --securityopt apparmor=unconfined ubuntu bash

By creating a new cgroup, enabling cgroups notifications on release, and specifying the release_agent script to be executed (once all processes within the same cgroup are killed) an attacker can execute code on the container's host.

There is no syntactic connection between the attack commands and the Docker configuration in Listing 1 so that a *semantic signature* of the Docker configuration is needed.

1"the stress test for banks is used to assess their resilience to adverse economic and market developments and contributes to the assessment of systemic risk" [3].

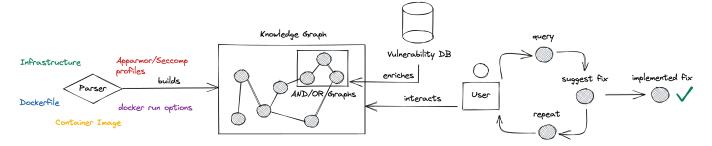


Fig. 1. The workflow of the stress-test methodology on Docker containers.

To exploit this technique, a container must either run as privileged or with a root user (by default on Docker), with CAP_SYS_ADMIN capability granted and mount syscall allowed. By foiling any (or all) preconditions the attack will fail. For example, one could just drop all capabilities (i.e. --cap-drop ALL). Yet this is hardly a side-effect free solution. By dropping the unconfined AppArmor profile users will find themselves trapped with a lengthy debugging of possible calls to network sockets of applications that don't work and each of which must be individually configured, debugged, and profiled². Similarly, in March 2022, a vulnerability affecting the Linux kernel leading to privilege escalation was discovered, namely, CVE-2022-0492 [5]. Again, this vulnerability exploits a vulnerable implementation of the release agent binary executed once all processes belonging to a cgroup are killed. For this vulnerability to be exploitable, one must run a container as a root user (or with the CAP DAC OVERRIDE capability), with mount and unshare syscalls allowed; obviously, containers with more permissions (e.g. privileged or with the CAP_SYS_ADMIN capability) are also affected. The key observation is that if the configuration is changed the vulnerable binary can stay as it is because the attack is no longer possible.

III. RELATED WORK

Access control and network security policies for cloud deployment are well studied by providing either access control solutions [6], [7], [8], [9] or by supporting the automated policy generation from given specifications [10], [6], [11]. Recent works also provide mechanisms for formal verification of microservice deployments [12], or continuous assessment methodologies [13]. Yet, the automatic or even computer-aided exploration and validation of configuration policies as available in practical deployments (e.g. combinations of Docker commands) and their subsequent testing, still remain largely unexplored in the academic literature.

Microservice Attack Generation Ibrahim et al. [14] investigated (theoretical) attacks on microservices by using vulnerabilities identified in a deployment to build an attack graph of all possible attacks. Whether these attacks are actually possible has not been tested. Also this analysis cannot be

readily translated to changes into a practical configuration (e.g. drop the CAP SYS ADMIN option).

Security industrial tools offering different kinds of 'vulnerability scans' and 'static analysis' for cloud environments are also available on the market. Yet, while they all 'formally' meet NIST definition of vulnerability scanning ('a technique used to identify hosts attributes and associated vulnerabilities' [15]) their actual operation is not what a security expert would intuitively expect even from the classical nmap network scanner [16] and even less of what one would expect from a static analyzer for software security [17].

Configuration analyzers (e.g. snyk ³ and Docker Bench ⁴) analyze configuration files and settings and check them against common or custom security best practices and policies (e.g. compliance with the CIS Benchmarks), some of these tools only provide compliance tests.⁵

Vulnerability Scanners (e.g. Clair ⁶ and Trivy ⁷) typically retrieves a software bill of material (SBOM) gathering all software packages used in an image or in configuration files and compares them against vulnerabilities repositories (e.g. NVD⁸ or Debian Security Bug Tracker⁹) to check if the current version of a package in use is *reported to be* vulnerable.

Such tools often generate false alerts as they are based on the same overcautious vulnerability reporting that is well known in secure software engineering for the analysis of vulnerabilities in open source libraries [18], [19].

Automatically suggesting a "fix" for a particular (cloud) misconfiguration is, to this day, an open problem. All previous tools do not suggest or provide any fix for detected vulnerabilities, leaving up to the end user the mitigation process to eliminate the alerts. To this extent, we will use the Analytic Hierarchy Process (AHP) [20], which has been used for decades by nearly all decision making disciplines, including graph theory and requirements engineering.

Knowledge graphs for cybersecurity. The use of graphs to investigate the security properties of cloud environments

²https://ubuntu.com/server/docs/security-apparmor

³https://snyk.io/product/container-vulnerability-management/

⁴https://github.com/docker/docker-bench-security

⁵E.g. terrascan by Accurics, built on top of OPA, and Bridgecrew, which are open source, along with CIS-CAT Pro, and Lacework which are commercial.

⁶https://github.com/quay/clair

⁷https://github.com/aquasecurity/trivy

⁸https://nvd.nist.gov/

⁹https://security-tracker.debian.org/tracker/

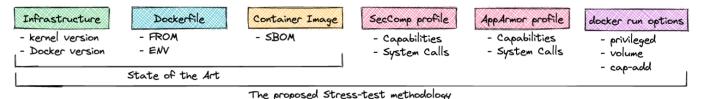


Fig. 2. The parsed configuration files to build the knowledge graph.

have already been investigated in the past. Yet, most existing approaches use knowledge graphs for security awareness, and intelligence sharing [21], [22], rather then security analysis of configurations. A comprehensive review can be found in [23].

The closest work is by Banse et al. [24] who build a Cloud Property Graph (CloudPG) using both static code analysis and an ontology; similarly to our idea, they propose an analysis framework to query the graph for security issues but focuses on bridging the gap between static code analysis of the application and its runtime environment. While the outcome is a sophisticated analysis of data flow leaks, this approach requires full access to the application code. Our approach complement this work by going in the opposite direction towards the analysis of deployment information to suggest alternative, safer, configurations.

IV. BUILDING THE GRAPHS

The methodology for capturing and analyzing cloud containers configuration by a knowledge graph where undirected edges and nodes are labeled to represent the container system objects and their relationships.

Build the knowledge graph. We parse the configuration files to represent the infrastructure on which the container engine is running (e.g. Ubuntu VM), the container engine being used (e.g. Docker), the container image (e.g. Dockerfile), and finally, the docker run options that will be used to run the container (e.g. privileged, volume, and user) along with the security profiles (e.g. AppArmor and Seccomp files). We then map these objects to node and their logical relations to edges in the graph (e.g., Container (node) has capability (edge) SYS_ADMIN (node) or $Docker_Engine$ (node) is using (edge) Kernel (node) of version (edge) 4.9 (node)).

In addition, we do not only model the current configuration (as parsed) but also possible configuration *alternatives*. For instance, we add nodes representing alternative versions of the Linux kernel or Docker engine.

We choose the Neo4J graph database to represent the knowledge graph and vulnerabilities dataset (AND/OR graphs) and the Python language to parse configuration files and automatically update the graph using Neo4J APIs.

In order to build the knowledge graph, we first parse the container configurations files. In particular, Fig. 2 shows the different files that we parse (e.g., we also consider security profiles and docker run options), and the information extracted from each, to build the knowledge graph.

State of the art tools do not parse the given permissions (e.g. Linux capabilities and system calls) and the docker run options for possible misconfigurations. For example, Dockerfile instructions can be overwritten by docker run options, thus it is important to parse all configurations available.

Build vulnerabilities graphs We enrich the graph with a dataset of known vulnerabilities and misconfigurations [25].

We use a two-dimensional taxonomy to classify container vulnerabilities and misconfigurations, slightly based on the attack taxonomy proposed in [26]. Within the first dimension we classify the vulnerabilities in three categories based on the affected component, namely, *Container*, *Kernel*, and *Engine*. Within the second dimension, we classify the vulnerabilities based on the MITRE ATT&CK tactics and techniques (e.g. privilege escalation and network service scanning) [25].

We represent each vulnerability in the graph as an AND/OR graph, where the root is the final goal of the attack, the rest of the nodes represent the attack assumptions that must hold for an exploit. For example, we use an OR node to represent a set of vulnerable versions (e.g. Linux kernel versions between 5.1 and 5.9) of a component that can be exploited. Based on the running configuration (infrastructure, container engine, etc.), represented in the knowledge graph, we then link the latter to AND/OR graphs assumptions being currently used (e.g., Container (node) has capability (edge) SYS_ADMIN (node) assumption of CVE - xxx - xxx (node)).

The vulnerabilities dataset is represented using a JSON file; in particular, Listing 2 shows the JSON representation of the first container escape described in §II.

V. SEARCHING FOR A FIX

Analytic Hierarchy Process (AHP). The AHP is a multiple criteria decision-making methodology. In AHP, a hierarchy of solution alternatives is created, then the user is asked to provide weights to each solution alternative, and finally, pairwise alternatives are compared until the optimal solution is obtained [27]. Before evaluating the presence of vulnerabilities within the graph, we interact with the end-user to rank the list of possible fixes that can mitigate the attacks. For instance, we may ask a user to assign a preference (with 1 least favorite and 9 most favorite) to run a container as not root or assign a preference to remove specific capabilities of the container. In practice this means ordering the following list of possible fixes: (version upgrade, not privileged, not root, not capability, not_syscall, read_only_fs, no_new_priv). Similar dimensions can then be used on different types of fixes. This ranking will help us in suggesting the most effective fix that, at the same time, the user is also most willing to accept and implement.

Test & Fix for vulnerabilities. Finally, we test (by querying the graph) and fix (by suggesting and eventually implementing security fixes) the system. To this aim, we rely on the user to accept the best alternative configurations (based on the provided weights). An attack is mitigated by implementing a fix (invalidating one attacks' assumption) which is reflected in the graph by removing or adding an edge.

Algorithm 1 shows the procedure to stress-test a cloud system by unveiling the presence of one vulnerability. The steps of the algorithm are (1) parsing the configuration files and building the knowledge graph, (2) adding and link the vulnerability AND/OR graph, (3) fetching user preferences, and finally (4) suggesting the best fix. To this aim, the algorithm iteratively suggests security fixes to mitigate the vulnerability assumptions, following the user preferences. Eventually, the algorithm can automatically accept the most preferred fix.

Algorithm 1 Stress-test a cloud system for one vulnerability.

```
Require: Configuration files
Require: Vulnerability
Ensure: Safe configuration
 1: Build Knowledge graph;
 2: Enrich the graph with the vulnerability;
 3: Get list of user preferred fixes;
 4: GET_PREFERRED_FIX(vuln_query)
 5: function GET_PREFERRED_FIX(vul_query)
       while vuln\_query == true \ do
 6:
           Collect vulnerability assumptions;
 7:
           Order assumptions by AHP;
 8:
           repeat
 9:
10:
              Suggest assumption to remove;
              if user_accepts_fix then
11:
                 remove edge;
12:
13:
           until user_not_happy
```

The configuration of more realistic cloud deployments may contain several vulnerabilities. In this case, the problem requires finding a globally optimal solution. Therefore, local fixes must be additionally weighted in combination with other misconfiguration fixes. Currently, our algorithm relies on user input to determine such weights based on AHP. Our implementation could be extended in the future to find a set of globally optimal fixes.

In some cases, the user can also decide to intentionally keep a few low-risk vulnerabilities to avoid trading off the performance of the system. In such cases, although the vulnerability query will still be satisfied, this approach may help move towards a "safer" configuration state (e.g. by running a container with all and only needed capabilities and system calls, instead of privileged).

We provide Neo4J queries examples in the *Preliminary Validation* paragraph of §VI.

VI. PRELIMINARY EVALUATION

We investigated the cost of storing the representation of container configurations (incl. configuration alternatives) and the memory requirements for storing vulnerabilities in the knowledge graph. In addition, we illustrate the feasibility of the proposed approach on three vulnerabilities.

The cost of storing containers. Tab. I shows the cost, in terms of number of nodes and edges, of storing a container image and several containers (using the Docker default security profile, with a subset of capabilities and system calls allowed). Specifically, we use one node to represent the host virtual machine, 50 nodes to represent the versions of Linux kernel (from version 3.9, released after March 20 2013, when Docker was released), one node to represent the Docker engine, 132 nodes to represent the versions of <code>Docker</code>, 83 nodes to represent the versions of <code>containerd</code>, and 18 nodes to represent the versions of <code>runc</code>. In addition, we use 41 nodes to represent Linux capabilities and 364 nodes to represent Linux system calls.

This amounts to 691 nodes and 6 relationships (first row in Tab. I). Additional nodes are used to represent container permissions, security profiles, and Docker run options; for example, custom security profiles (e.g., user-defined AppArmor profiles), may require additional nodes and relationships corresponding to the granted capabilities and system calls, as well as relevant Docker run options (e.g., --user and --volume).

TABLE I
THE COST OF STORING CONTAINER IMAGES AND (DEFAULT)
CONFIGURATIONS INTO THE KNOWLEDGE GRAPH.

Object/s	#_Nodes	#_Edges
Initialization	691	6
1 Image	693	8
1 Container (default)	702	349
100 Container (default)	999	1.339
1.000 Container (default)	3.699	10.339

In the previous table, we considered all containers to be instantiated from different images, thus with two additional

nodes and relationships. Overall, the number of nodes and edges in the knowledge graph does not grow exponentially. This is promising as it would allow us defining efficient algorithms to suggest the best security fixes.

Tab. II shows different Docker run options with the corresponding number of edges; the number of nodes in the graph remains the same.

TABLE II
LIST OF POSSIBLE DOCKER RUN OPTIONS WITH THE CORRESPONDING
NUMBER OF EDGES.

Docker run options	#_Edges
cap-drop ALLcap-add NET_BIND_SERVICE	335
cap-add NET_ADMINsecurity-opt apparmor=unconfined	348
privileged	420

Additional configurations exist, as a combination of adding and removing capabilities, granting or denying system calls (within *AppArmor* or *SecComp*), not using the root user or a read-only filesystem.

The cost storing vulnerabilities. Tab. VI presents the dataset of vulnerabilities we collected from different sources, along with the number of nodes and edges needed to represent them. The number of nodes and edges in the table corresponds to the AND/OR graph representing each vulnerability; for example, in the graph there is a node presenting each Linux kernell version, and for a kernel vulnerability, there will be an edge between the vulnerability and each vulnerable version. We classify vulnerabilities in three categories, namely, container profile misconfigurations, Linux kernel bugs, and container engine vulnerabilities, as suggested in [28]. Within each category, we have a subcategory representing the impact of each vulnerability or attack based on the MITRE ATT&CK tactic and techniques for containers [25]. For the validation of our stress-test approach, we retrieved a set of vulnerabilities belonging to each category. In particular, for container profile misconfigurations we retrieved 6 escaping attacks, for Linux kernel bugs we retrieved 24 CVEs (only 10 shown in Tab. VI), mostly from [26] and, finally, for container engine vulnerabilities, considering only Docker (or Docker subcomponents, such as *runc* and *containerd*), we retrieved 6 CVEs from [28]. In total, our dataset contains 36 vulnerabilities.

Vulnerabilities Queries. To illustrate the feasibility of our approach, we performed an initial evaluation on three vulnerabilities, namely, *Cgroup escape*, *CVE-2022-0492*, and *CVE-2020-13401* (green rows in Tab. VI). To the best of our knowledge, an existing algorithm to traverse AND/OR graph in Neo4j does not yet exist. Therefore, for our initial validation, we manually check whether a vulnerability is exploitable or not. In future work, we plan to implement such an algorithm to automatically check the presence of vulnerabilities. Listing 3 shows a Neo4J query to check

TABLE III
INFORMATION ABOUT THE VULNERABILITIES DATASET, DIVIDED BY CATEGORIES, TOGETHER WITH THE NUMBER OF NODES AND EDGES.

Categ.	Sub-cat.	CVE	#_Nodes	#_Edges
		Cgroup escape	8	12
Container misc.	Escape to host	Cap. SYS_MODULE	6	7
		Kernel fs /sys	2	2
		Host devices	7	11
		Host /root	4	6
		Docker socket	4	6
		CVE-2022-0847	11	19
		CVE-2022-0492	58	62
Kernel bugs	Exploitation	CVE-2022-0185	22	25
		CVE-2020-14386	44	44
		CVE-2017-7308	47	47
		CVE-2017-5123	10	10
		CVE-2016-8655	37	40
		CVE-2016-4997	20	20
		CVE-2017-6074	23	23
		CVE-2017-1000112	27	27
Docker vuln.	Code injection	CVE-2019-14271	9	14
	Exploitation	CVE-2020-15257	106	109
	Escape to Host	CVE-2016-9962	27	29
		CVE-2018-15664	66	66
	10 11081	CVE-2019-5736	299	300
	DoS	CVE-2020-13401	221	224

whether a certain property (e.g., permission, capability, or system call) belongs to a container or not.

```
Listing 3. Neo4J query to check a container relationship MATCH (c:Container {name: "Nginx"})
MATCH (p:Permissions {name: "Privileged"})
RETURN EXISTS( (c)-[:HAS]-(p)
```

Based on the current implementation, as future work, we plan to test this approach on all 36 vulnerabilities with different configurations (different security profiles, docker run options, etc.) and possibly, on different container engines. By doing so, we can evaluate more extensively the results of stress-tests and explore the support of what-if scenarios; for example, we can claim the most effective mitigation against most attacks but also evaluate the most dangerous configurations. Finally, at the end of each run, the number of removed edges (attacks assumptions) could be used as an indicator of the resilience to the stress test and can be used as a measure of quality in the context of a more comprehensive validation.

VII. DISCUSSION

This approach might also be suitable to build attack paths in more complex environments (e.g. Kubernetes clusters).

Efficient graph algorithms could be used to cast and then address a number of security issues: reachability (e.g. given the current configuration, whether the attacker can reach a new state), minimum weight traversal (e.g. the easiest exploitation path), and vertex cuts (e.g. suggesting a policy or configuration change that invalidates an attack).

To have a dynamic picture, one could run the stress-test at a given time interval and evaluate the output at each time; for example, we could evaluate the number of changes in the graph (new nodes or edges) as a risk analysis of the the current configuration, or the number of changes needed to get to a "safe" state.

We plan to extend our implementation and support more container engines (e.g. Podman and CRI-O) as well as infrastructure-as-code tools (e.g. Vagrant and Terraform) integrate the implementation into a container orchestration tool (e.g. in Kubernetes as an admission controller).

VIII. CONCLUSION

In this paper, we proposed a stress-test approach for cloud configurations, by using a knowledge graph to represent deployments and permissions, and AND/OR graphs to represent vulnerabilities. We described our solution along with algorithms to unveil vulnerabilities and semi-automatically suggest security fixes to mitigate them; we also described a first implementation and evaluation on Docker containers. We believe this is the first step forward towards a dynamic and continuous evaluation mechanism for risk analysis in cloud environments while suggesting security fixes. In the future, more validation on scalability and query performance is needed, especially with hundreds or thousands of containers.

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