

Attack Graph Generation for Microservice Architecture

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ABSTRACT

Microservices, ~~which are typically technologically heterogenous and can be deployed automatically,~~ are increasingly dominating ~~the field of~~ service systems, ~~among their many characteristics are technology heterogeneity, communicating small services, and automated deployment.~~ ~~Therefore, However,~~ with the ~~increase~~increased utilization of ~~utilizing~~third-party components distributed as images, the potential vulnerabilities ~~existing in a~~microservice-based ~~system~~systems increase. Based on ~~components~~component dependency, ~~these~~such vulnerabilities ~~may~~can lead to exposing ~~a system's~~critical assets ~~of systems~~. Similar problems have been ~~tackled in~~addressed by the computer networks ~~communities~~community. In this paper, we propose ~~the utilization of~~utilizing attack graphs ~~as a part of~~in the continuous delivery infrastructure ~~used in of~~microservices-based systems. To that end, we relate microservices to network nodes and automatically generate attack graphs that help practitioners ~~to~~identify, analyze, and prevent plausible attack paths ~~on~~in their microservice-based container networks. We present a complete solution that can be easily embedded ~~into the~~in continuous delivery systems; and ~~show with real-world use cases~~demonstrate its efficiency and scalability ~~based on real-world use cases~~.

Comment [Editor1]: Remark: Do you mean “micro”? Please clarify.

KEYWORDS

Attack Graph Generation, Microservices, Containers ACM Reference Format:

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1 INTRODUCTION

Microservices, a recent approach to ~~manage~~managing the complexity of modern applications, are increasingly ~~being~~adopted in real-world systems. ~~The new architectural style follows~~Microservice architectures follow the ~~foundational~~fundamental principle of Unix ~~that decomposes,~~ i.e., systems ~~are decomposed~~into small programs [33], each ~~fulfills only one~~performing a single cohesive task ~~and, However, such programs~~ can work together ~~using~~via universal interfaces. ~~Each, where each~~ program is a microservice that is designed, developed, tested, deployed, and scaled independently [16]. ~~The smaller~~Smaller decoupled services have a positive impact on some system qualities ~~like, such as~~scalability, fault isolation, and technology heterogeneity [26]. ~~However,~~ however, other qualities ~~like the, such as~~network utilization and ~~the security,~~ can be

affected negatively affected [3]. Balancing the trade-off among these factors derive the The decision of using to use microservices in industry-industrial applications must consider the tradeoffs among these factors. That said, a none-exhaustive list¹ shows a significant shift by many enterprises across of companies from different domains towards using that use microservice-based architecture: indicates a significant shift towards their use. This shift is primarily motivated mainly by the demanding

requirements of scalability, time to market, and better-improving development optimization of development efforts. We see microservice Microservice-based systems can be seen in various domains of, such as video streaming, social networks, logistics, the Internet of things Things [9], smart cities [23], and security-critical systems [15].

The utilization of microservices has popularized two main concepts in the software engineering community. The first is the container-based deployment, in which the where new small services are shipped and deployed in containers [19]. As a result, the such systems are deployed as networks of communicating microservices. For Due to their lightweight and open system level virtualization [7], the containerization frameworks like, such as Docker [10], are have become a high-performance alternative to hypervisors [22]. The second often-used concept in the domain of microservices development is DevOps (developer operations) [10]. DevOps, which enable practices in which full automation of that can fully automate the deployment process is achieved. In the course of this. Here, end-to-end automated packaging and deployment is a vital part component of microservices microservice development. In addition to the agility and optimization brought realized by the these two concepts, significant concerns around have been raised about their impact on security [3]. arise. These concerns are motivated by the increasing number of communication end points points among the microservices, the potentially growing increasing number of vulnerabilities emerging from open-source DevOps tools and third-party frameworks distributed by Docker hub [17, 32], and the weaker isolation (than compared to hypervisor-based virtualization) between the host hosts and the container since containers because all containers share the same kernel [7, 8]. In this paper, we tackle address the problem of analyzing the security of the container networks using threat models [21]. Following the DevOps mentality, we propose an automated method that can be integrated into continuous delivery systems to generate attack graphs.

Security threat models are widely used to assess threats facing to a system [21]. Not only are they appealing to the They appeal to practitioners as because they provide a visual presentation presentations of possible attack paths on in a system, but They also appeal to scientists since because they are well formalized (syntax and semantics) [20, 24]. Such formalism enables quantitative and qualitative analysis of the risk, cost, and likelihood of the attacks, which affect the defense strategy strategies. In computer networks, attack graphs [27, 31] are the dominant threat model used to inspect the security aspects of a network. They help analysts to carefully analyze system connections and detect the most vulnerable parts of the system. An attack graph depicts the actions that an attacker may use to reach their goal. Typically, experts (e.g., red teams) manually

Comment [Editor2]: Remark: Please consider defining containers specific to this context.

Comment [Editor3]: Tip: Word and phrase choice: In academic writing, information is presented with accuracy and conciseness. Formal language is a hallmark of academic English. One way to ensure conciseness in expression is converting phrasal verbs to formal words. Hence, we have changed “brought” to “realized.”

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construct attack graphs. ~~The manually; however, this~~ manual process is time-consuming, error-prone, and does not address the complexity of modern ~~infrastructure~~infrastructures.

Previous ~~work-has~~studies have dealt with automatic attack graph generation, ~~exclusively-in~~for computer networks [18, 27, 31]. In these networks, an attacker performs multiple steps to achieve ~~his~~their goal, e.g., gaining the privileges of a specific host. Tools that scan the vulnerabilities of a particular host ~~are available~~ [14], ~~but~~; however, they are ~~not sufficient~~insufficient to analyze the security of an entire network, and the possible composition of various vulnerability exploitation as an attack path [31].

To the best of our knowledge, ~~an~~-automated attack graph generation for microservice architectures ~~was~~has not ~~tackled~~been examined by ~~any~~ previous ~~work~~studies. To that end, ~~in this paper~~, we extend the advancementadvancements made

<https://microservices.io/articles/whoususingmicroservices.html>

in the computer networks field to the [microservice](#) domain ~~of microservices~~. ~~Therefore the contribution~~. [The primary contributions](#) of this paper ~~is~~[are summarized](#) as follows.

- We propose attack graphs as a new artifact ~~of the~~ [for](#) continuous delivery systems. We present an approach, based on methods from computer networks, to automatically generate attack graphs for microservice-based architectures ~~that are~~ deployed as containers.

- We present the technical details of an extensible tool that implements ~~our~~ [the proposed](#) approach. ~~The~~ [Note that this](#) tool is available online².

- ~~An~~ [We provide an](#) empirical evaluation of the efficiency of ~~our~~ [the proposed](#) tool ~~is relative to~~ generating attack graphs ~~of for~~ real-world systems.

The ~~structure~~ [remainder](#) of this paper is [organized](#) as follows. We introduce ~~the~~ preliminaries ~~needed for this paper~~ in Section 2. ~~We, then, Then,~~ [we](#) present ~~our~~ [the proposed](#) approach in Section 3, ~~and its~~. [An](#) evaluation [of the proposed approach is given](#) in Section 4. We discuss related work in Section 5. ~~Lastly, conclusions~~ [Conclusions](#) and [suggestions for](#) future work are discussed in Section 6.

2 BACKGROUND

We ~~start by introducing~~ [introduce](#) the concept of microservices, their benefits, and security implications in Subsection 2.1. In Subsection 2.2, we look into vulnerability scanners as tools to scan a single host for vulnerabilities. In Subsection 2.3, we introduce and formally describe attack graphs as methods to diagnose [the](#) security weaknesses of a given system ~~composed of~~ [comprising](#) multiple hosts.

2.1 Microservices

As real-world software ~~grows~~ [increases](#) in size, there is an ~~ever~~-increasing need to decompose ~~it~~ [software](#) into an organized structure to promote ~~scaling, reuse~~ [scalability, reusability](#), and readability. A software application ~~whose~~ [with](#) modules ~~that~~ cannot be executed independently is ~~called~~ [referred to as](#) a monolith. Monolithic systems are characterized by tight coupling, vertical scaling, and strong dependence [16]. ~~The~~ Service Oriented Architecture (SOA) addresses these issues by restructuring its elements into components that provide services ~~which~~ [that](#) are used by other entities ~~through~~ [via](#) a networking protocol [29]. However, in a typical SOA, the services are monolithic, which gives rise to the concept of microservices to provide ~~an~~-even more fine-grained task separation [3]. The ~~novel~~ term "microservices" was first introduced in 2011 at an architectural workshop ~~to propose~~ [as](#) a common term ~~for~~ [to describe](#) the ~~explorations~~ [work](#) of multiple researchers [13, 16]. In the microservices paradigm, multiple services are split into very basic ~~units which are task-oriented~~ [units](#). According to Dragoni et al., a microservice is a cohesive, independent process interacting via messages. These microservices constitute a distributed architecture called a microservice architecture [13]. Microservice architectures ~~benefit us with the advantage of having~~ [have](#) more heterogeneous technologies, cheaper scaling, resilience, organizational alignment, and composability [26]. However, they add additional complexity and have a wider attack surface as the need for many services to communicate with each other and third-party software increases [11,13]. While microservices are an architectural

Comment [Editor4]: Remark: Please consider revising this to "approach" here and at all such instances for consistency.

principle, container technology has emerged in cloud computing to provide a lightweight virtualization mechanism. ~~This~~ Container technology enables microservices to be packaged and orchestrated through the


Cloud [28].

2.2 Vulnerability Scanners

A vulnerability is a system weakness that ~~could~~can be exploited by a malicious actor with the help of an appropriate suite of tools. Many vulnerabilities are publicly known (such as those in the Common Vulnerabilities and Exposures (CVE) list) and organized in databases like, such as the National Vulnerability Database (NVD). CVE² is a list of publicly known cybersecurity vulnerabilities where each entry contains an identification number, a description, and at least one public reference. This list of publicly known vulnerabilities is organized in the NVD³ repository ~~that, which~~ enables automation of vulnerability management, security measurement, and compliance [6]. Vulnerability scanners ~~try~~attempt to detect weaknesses by scanning a single host and generating a list of exploitable vulnerabilities [12, 14]. However, ~~since~~more sophisticated approaches are required because many attacks are network-based and performed in multiple steps ~~through~~throughout a network; ~~more sophisticated approaches are required,~~. Therefore ~~a combination,~~ combinations of a vulnerability ~~scanners~~scanners and ~~topology is seen as~~ at topologies are considered promising ~~solution~~solutions to this problem ~~in previous work~~ [18, 31].

2.3 Attack Graphs

Attack graphs [31] are a popular way ~~of examining~~to examine network security weaknesses. They ~~help analysts to analyze~~facilitate careful analysis of a given system and ~~detect~~detection of its vulnerable ~~parts~~carefully-components. The definition of an attack ~~graphs~~graph may vary; ~~but, however,~~ it is essentially a directed graph ~~that consists of~~comprising nodes and edges with various representations.

Seyner et al. ~~defined~~defined an attack graph as a tuple of states, transitions between the states, ~~an~~initial state, and ~~a~~success states. An initial state represents the state from ~~where~~which the attacker ~~starts~~thebegins an attack and through a chain of atomic attacks ~~tries~~atte~~pt~~reach one of the success states [31]. Ou et al. ~~introduce~~introduced the notion of a logical attack graph. ~~A logical attack graph, which is a~~  ~~dynamic~~ directed graph that ~~consists of two kinds of nodes: comprising~~-fact-nodes and derivation nodes. Each fact node is labeled with a logical statement in the form of a predicate applied to its arguments, while each derivation node is labeled with an interaction rule ~~that is used~~forin the derivation step. The edges in ~~the~~a logical attack graph represent a "depends on" relation [27]. Ingols et al. ~~make~~made a distinction between full, predictive, and multiple-prerequisite (MP) attack graphs. ~~Full~~A full graph is a directed acyclic graph ~~that consists of~~comprising nodes that represent hosts and edges that represent vulnerability instances. Predictive attack graphs use the same representation as full attack graphs, with the only difference lying in the

Comment [Editor5]: Remark: How many "states" are included in this definition? Please clarify.

²<https://cve.mitre.org/>
³<https://nvd.nist.gov/>

constraint of when the edges are added to the attack graph. ~~These~~[Note that predictive](#) graphs are generally smaller than full graphs. [An](#) MP attack is an attack graph with ~~as~~ contentless edges and ~~three node type~~-state nodes, vulnerability instance nodes, and prerequisite nodes [18].

In this paper, we define an attack graph ~~to be~~[as](#) a directed acyclic graph with a set of nodes and edges similar to the full graph representation ~~of~~[proposed by](#) Ingols et al. [18]. As an expansion to this model, a node represents ~~a~~[the](#) state of a host with its current privilege. ~~An, and an~~ edge represents a successful transition between two such hosts. We can ~~think of~~[consider](#) an edge as a successful vulnerability exploitation ~~which is~~ initiated from a host with a required privilege to another or the same host with ~~the~~[a](#) newly gained privilege as a result of the vulnerability exploitation. To the best of our knowledge, attack graphs ~~are~~[have been](#) used for networks but not microservices, potentially because there is ~~no~~[currently no existing](#) tool support.

²The link is omitted for anonymization purpose

3 METHOD

We already defined an attack graph. Now, In Subsection 3.1, we look at discuss how the existing components of attack graph generation for a computer network map into are mapped to a microservice environment, we illustrate and the concepts are illustrated using a small example in Subsection 3.1. Then, in Subsection 3.2, we present the tools that we use to achieve this mapping and give provide an overview of our the proposed system and its components: i.e., the Topology Parser in (Subsection 3.2.1), the Vulnerability Parser in (Subsection 3.2.2), and the Attack Graph Generator (Subsection 3.2.3). In addition, with the Breath-first Search (BFS) graph traversal algorithm is discussed in Subsection 3.2.3.

3.1 From Network Nodes to Microservices

In our work this study, we adapt already existing attack graph generation methods from the computer networks field to the microservices ecosystem. In order to do To accomplish this, we identify the corresponding components and find identify an equivalent replacement that can be used in a microservice architecture. In this subsection, we start first begin by introducing the Docker framework and its terminology. We then discuss the attack graph concepts mentioned in Subsection 2.3: that fit our use case. We illustrate the whole idea overall concept by demonstrating a small example.

Docker is one of the most popular and used containerization frameworks currently available. In Docker, a distinction is being made between the terms *image*, *container*, and *service*. An Here, an *image* is an executable package that includes everything needed required to run an application, a *container* is a runtime instance of an image, and a *service* represents a container in production. A service only runs one a single image, but, however, it codifies the way that image runs, what ports it should use, and how many replicas of the container should run so the service has the capacity it needs requires [25]. In our work, we We construct attack graphs by statically analyzing the topology of the containers. Hence, therefore, we treat these terms equally.

Privileges play a central role in the generation of attack graphs. Traditionally, the privileges are modeled as a hierarchy that varies in the access level (*User*, *Admin*) and the access scope (virtual machine VOS, host machine OS). The exhaustive list of privileges that are used in this paper are *None*, *VOS*, *VOS(Admin)*, *OS(User)*, and *OS(Admin)*. VOS means that the privilege is exclusive to a virtual machine, while not affecting the host machine. However, in our case, unlike hosts in a network, these privileges refer to images and not virtual machines. On the other side, the *The OS* keyword *OS* means that a user who has this privilege can control the host machine. Since *VOS* *OS* are isolated from host machines and their exploitation does not imply the exploitation of the host machine, they are in at the lower level of the hierarchy [4]. *None* means that no privilege is obtained, *User* means that only a subset of user level privileges are is granted, and *Admin* grants control over the whole system.

As mentioned earlier, the previously, *nodes* and *edges* are the basic building blocks of an attack graph. A *node* represents a combination of a compromised Docker image and a certain privilege gained by the attacker after exploiting a vulnerability. A directed *edge* between two nodes

represents an attack step from one node to another ~~node~~ (adjacent exploitable image with the gained privileges). Each edge is typed with the vulnerability (CVE) that could be exploited in the end node.

For attackers to exploit a given vulnerability, they ~~need to~~ must have certain *preconditions*, i.e., the minimum ~~required~~ privileges ~~required~~ to exploit [4]. Once ~~an attacker meets these preconditions and exploits the vulnerability, he gains~~ they gain the privilege of the end node as a *post-condition*, and a directed edge is added between ~~them~~ [Both the ~~pre-preconditions~~ and postconditions in this ~~work~~ study are transformed from ~~pre-precondition~~ and postcondition ~~manually selected and evaluated by experts in existing work~~ [4]. The ~~pre-precondition~~ and postcondition rules use the fields defined by ~~the~~ NVD, as well as an occurrence of specific keywords from ~~the~~ CVEs ~~CVE~~ descriptions [6].

Comment [Editor6]: Remark: Please clarify what "them" refers to.

3.1.1 Example. ~~In order~~ Here, we present a small example to ~~show~~ demonstrate how the attack graph generation works in practice; ~~we present a small example.~~ The example is taken from the Netflix OSS ~~GitHub~~ ~~GitHub~~ repository. ~~The~~ Netflix OSS example is a Spring Cloud-based ~~microservices~~ ~~microservice~~ architecture that uses the following microservices: Service Discovery (Eureka), Circuit Breaker (Hystrix), Intelligent Routing (Zuul), and Client Side Load Balancing (Ribbon). ~~Displayed in~~ Figure 1a ~~is shows~~ a subset of the example topology, where each node denotes a container and each edge is a connection between two containers if one calls the other. The topology ~~consists of~~ ~~comprises~~ an "Outside" node; ~~and a~~ "Docker daemon" node, ~~as well as~~ Zuul, Eureka, and other nodes. According to Netflix, Zuul is an edge service that provides dynamic routing, monitoring, resilience, and security functionalities. Eureka is a ~~REST~~ ~~(Representational State Transfer)~~-based service ~~that is~~ primarily used in the cloud for locating services for ~~the purpose of~~ load balancing and fail-~~over~~ middle-tier servers. ~~In~~ Figure 1b ~~we can see shows~~ a part of the ~~corresponding~~ ~~corresponding~~ attack graph, where a node is a pair of the image and its privilege, while an edge represents an atomic attack. Parts of both graphs have been ~~omitted~~ intentionally ~~omitted to reduce complexity for simplicity~~. An example path ~~that~~ an attacker would take could be to first attack the Zuul container by exploiting the CVE-2016-10249 vulnerability by crafting an image file, which triggers a heap-based buffer overflow⁴ and gains ~~the~~ USER privilege. With this USER privilege, an attacker can exploit the CVE-2015-7554 vulnerability on the same container via crafted field data in an extension tag in a TIFF image⁵ to gain ~~the~~ ADMIN privilege. Once the ADMIN privilege has been obtained on ~~Zuul~~, the attacker can attack the Eureka container by exploiting CVE-2017-7600 via another crafted image⁶ and gain ~~the~~ ADMIN privilege. ~~It is important to note~~ ~~Note~~ that this is not the only path ~~that~~ the attacker can take ~~in order to~~ ~~have~~ ~~obtain~~ ADMIN privileges on ~~Eureka~~. Another path would be to exploit the CVE-2018-1124 vulnerability ~~via~~ ~~by~~ creating entries in the ~~file~~ ~~system~~ (procs) by ~~starting~~ processes, which could result in crashes or arbitrary code execution⁷. This vulnerability can be exploited by having only ~~the~~ USER privilege on Zuul to gain ~~the~~ ADMIN privileges of the Eureka container directly. Our attack graph generator shows both paths ~~since~~ ~~because~~ it is of interest to ~~see every~~ ~~identify all~~ possible ~~route in~~ ~~routes through~~ which a container can be compromised.

Comment [Editor7]: Remark: Please consider revising this to "the Zuul container"?

Comment [Editor8]: Remark: Please consider revising this to "the Eureka container"?

3.2 Attack Graph Generation for Docker Networks

⁴<https://nvd.nist.gov/vuln/detail/CVE-2016-10249>

⁵<https://nvd.nist.gov/vuln/detail/CVE-2015-7554>

⁶<https://nvd.nist.gov/vuln/detail/CVE-2017-7600>

⁷<https://nvd.nist.gov/vuln/detail/CVE-2018-1124>

Figure 2 ~~gives~~shows an overview of ~~the~~our attack graph generator. ~~In the figure, where~~ the rectangles denote the main system components ~~of the~~
system,



Figure 1: Reduced Netflix OSS example; (a) Example topology graph and (b) Example resulting attack graph

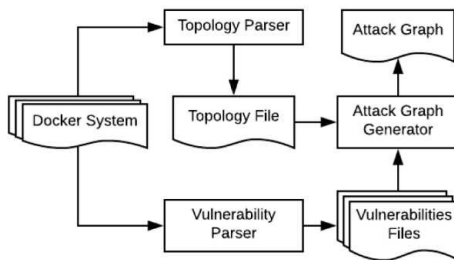


Figure 2: Overview of the Attack Graph Generator System

while the arrows describe indicate the flow of the system, and the files are the intermediate products. Our The proposed attack graph generator is composed of comprises three main primary components, i.e., the Topology Parser, the Vulnerability Parser, and the Attack Graph Generator. The Topology Parser reads the underlying topology of the system and converts it into a format needed for our required by the Attack Graph Generator, the The Vulnerability Parser scans the vulnerabilities for each of the images image, and the Attack Graph Generator generates the attack graph from the topology and vulnerabilities files. In the following subsections, we first have a look into examine the system requirements, and then describe each component in more details greater detail.

The proposed generator is was developed and tested for Docker 17.12.1-ce and Docker-Compose 1.19.0 [25]. Docker Compose⁹ is a tool for defining the orchestration of multi-container applications. #Docker Compose provides a static configuration file that specifies the system

Comment [Editor9]: Remark: Please verify our edit here.

Comment [Editor10]: Tip: Tense: In academic writing, the simple past tense is usually used in the Material and Methods/Experimental and Results sections of the research article.

containers, networks, and ports. Note that Clair and ClairCtl¹⁰ ~~are~~were used for ~~vulnerabilities~~vulnerability scanning. The generator ~~is~~was written in Python 3.6. Although we used specific versions of ~~the~~these tools, the pipe and filter structure of the generator can be easily extended to other versions of Docker-Compose, vulnerability scanners, and microservice architectures.

3.2.1 *Topology Parser*. To generate an attack graph ~~of~~for a given system, we ~~require an arrangement of~~must arrange its components and connections ~~described~~as a system topology. The topology of Docker containers can be described ~~either~~at runtime or at design time ~~by~~using Docker-Compose. In our case, ~~since~~we are doing-performing a static attack graph analysis, ~~thus~~we use-used Docker-Compose to extract the topology. Docker-Compose provides a file (docker-compose.yml) ~~which~~that is used to describe the orchestration of the services. ~~That is to say,~~the ~~In other words,~~this file already exists-anyways; ~~therefore,~~no further input is required from ~~the a~~a security analyst is required. However, different versions of the docker-compose.yml ~~file~~use different syntax. For example, older versions use the deprecated keyword "link~~_,~~" while newer ~~ones use~~versions exclusively use "networks~~_,~~" to denote a connection between two images. ~~We~~Here, we use the keyword "networks" ~~as an~~indicator that to indicate a connection between two images ~~exists~~.

~~In the majority of cases, for~~For an application to be useful in most cases, it communicates with the outside world, i.e., it has endpoints that can be used by ~~the~~an outer network. In Docker, this is ~~usually done~~typically accomplished by publishing ports. This is the case ~~in~~for both computer networks ~~as well as in~~and microservice architectures.

Another consideration ~~that we take into account~~is the privileged access⁸. ~~Some~~In order to function properly, some containers obtain certain privileges that grant them control over the Docker daemon ~~in order to function properly~~. For example, a user may want to run ~~some~~hardware (e.g., ~~web-cams~~webcam) or ~~some~~applications that demand higher privilege levels from Docker. In Docker, this is ~~usually done either~~typically ~~achieved~~by mounting the Docker socket or specifying the ~~keyword~~"privileged" ~~keyword~~in the docker-compose.yml file. ~~An~~Here, an attacker with access to these containers also has access to the Docker daemon. Once ~~the attacker has access to the Docker daemon,~~he has~~they have~~ potential access to the ~~whole entire~~microservice system, since every because each container is controlled ~~by~~by the daemon.

3.2.2 *Vulnerability Parser*. In the preprocessing step, we use Clair to generate the vulnerabilities ~~of~~for a given image. Clair is a vulnerability scanner that inspects a Docker image and generates its vulnerabilities by providing ~~the CVE-ID, a description and, which describes the attack~~vector for each vulnerability. An attack vector is an entity that describes which conditions and effects are connected to ~~this~~the given vulnerability.

⁸<https://docs.docker.com/compose-2/> ¹⁰<https://github.com/coreos/clair>

⁹<https://github.com/coreos/clair>

⁸ <http://obrown.io/2016/02/15/privileged-containers.html>

Comment [Editor11]: Remark: Please place footnotes appropriately here and at all such instances.

We collect the fields in the attack vector ~~which are~~, as defined by the ~~National Vulnerability Database(NVD)~~ [6], i.e., Access Vector (Local, Adjacent Network ~~and~~, Network), Access Complexity (Low, Medium, High), Authentication (None, Single, Multiple), Confidentiality Impact (None, Partial, Complete), Integrity Impact (None, Partial, Complete), and Availability Impact (None, Partial, Complete). Since Clair does not provide a command line interface to analyze a Docker image, we use Clairctl to analyze a complete Docker image.

```

Data: topology, cont, expl, priv, acc
Result: nodes, edges
1 nodes, edges, passed = nodes = [], [], []
2 queue = Queue()
3 queue.put("outside" + "ADMIN")
4 while ! queue.isEmpty() do
5     curr_node = queue.get()
6     curr_cont = get_cont(curr_node)
7     curr_priv = get_priv(curr_node)
8     neighbours = topology[curr_cont]
9     for nb in neighbours do
10         if curr_cont == docker_host then
11             end_nb = "ADMIN"
12             create_edge(curr_node, end_nb)
13         end
14         if nb == docker_host and priv_acc[curr_cont] then
15             end_nb = "ADMIN"
16             create_edge(curr_node, end_nb)
17             queue.put(end_nb)
18             passed_nodes.add(end_nb)
19         end
20         if nb != outside and nb != docker_host then
21             precondition = cont_expl[nb][precond]
22             postcondition = cont_expl[nb][postcond]
23             for vul in vuls do
24                 if curr_priv > precondition[vul] then
25                     end_nb = nb + postcondition[vul]
26                     create_edge(curr_node, end_nb)
27                     if end_node not in passed_nodes then
28                         queue.put(end_node)
29                         passed_nodes.add(end_node)
30                     end
31                 end
32             end
33         end
34     end
35     nodes = update_nodes()
36     edges = update_edges()
37 end

```

Algorithm 1: BFS algorithm for attack graph generation



Comment [Editor12]: Remark: Please check the position of Algorithm 1.

```

Data: topology, cont expl, priv acc
Result: nodes, edges
1 nodes, edges, passed nodes = [], [], []
2 queue = Queue()
3 queue.put("outside" + "ADMIN")
4 while ! queue.isEmpty() do
5     curr_node = queue.get()
6     curr_cont = get_cont(curr_node)
7     curr_priv = get_priv(curr_node)
8     neighbours = topology[curr_cont]
9     for nb in neighbours do
10         if curr_cont == docker_host then
11             end_nb = "ADMIN"
12             create_edge(curr_node, end)
13         end
14         if nb == docker_host and priv_acc[curr_cont] then
15             end_nb = "ADMIN"
16             create_edge(curr_node, end)
17             queue.put(end)
18             passed_nodes.add(end)
19         end
20         if nb != outside and nb != docker_host then
21             precondition = cont_expl[nb][precond]
22             postcondition = cont_expl[nb][postcond]
23             for vul in vuls do
24                 if curr_priv > precondition[vul] then
25                     end = nb + postcondition[vul]
26                     create_edge(curr_node, end_node)
27                     if end_node not in passed_nodes then
28                         queue.put(end_node)
29                         passed_nodes.add(end_node)
30                     end
31                 end
32             end
33         end
34     end
35     nodes = update_nodes()
36     edges = update_edges()
37 end

```

3.2.3 *Attack Graph Generator*. After the topology is extracted and the vulnerabilities for each container are generated, we ~~continue with~~ ~~the~~ proceed to attack graph generation. Here, we first ~~pre-process~~ preprocess the vulnerabilities and convert them into sets of pre-preconditions and postconditions.

~~In order to do~~ To achieve this, we match the previously acquired attack vectors ~~acquired earlier~~ from the vulnerability database and keywords of the descriptions of each vulnerability to generate attack rules. When a subset of attack vector fields and description keywords matches a given rule, we use the pre-precondition or postcondition of that rule. An example of a pre-precondition attack rule would be for a vulnerability to have

either "gain root" or "gain unrestricted shell access" or "obtain root" in its description and all of the impacts from the NVD attack vector [6] to be "COMPLETE" in order to gain/obtain the precondition OS(ADMIN) precondition [4]. If more than one rule matches, we take the one rule with the highest privilege level for the preconditions and the lowest privilege level for the postconditions. If no rule matches, we take None as the precondition and ADMIN(OS) as the postcondition. This results in a list of container vulnerabilities with their preconditions and postconditions.

Comment [Editor13]: Remark: Is this one item (separated by a comma) or two unique items? Please clarify.

Breadth-first Search. After the preprocessing step is done, the vulnerabilities are parsed and their preconditions and postconditions are extracted. Together with the topology, they are feed into a Breadth-first Search (BFS) algorithm. Breadth-first Search is a popular search algorithm that traverses a graph by first looking at the neighbors of a given node, before diving deeper into the graph. The pseudocode for our modified Breadth-first Search algorithm is given in Algorithm 1. This algorithm requires a topology, a dictionary of the exploitable vulnerabilities, and a list of nodes with privileged access as an input and the output is made up of comprises nodes and edges that make form the attack graph. Topology In Algorithm 1, "topology" (Subsection 3.2.1) provides the information about the connectivity between the containers, "cont_expl" (Subsections 3.2.2 and 3.2.3) contains information regarding about which vulnerabilities can be attacked (with their preconditions and postconditions), and "priv_acc" (Subsection 3.2.1) is the array of nodes that have with high (i.e., ADMIN) permissions to the Docker daemon. The first, the algorithm first initializes the nodes, edges, queue, and the passed nodes (Lines 1, 2). Afterward lines 1 and 2. Then, it generates the attacker node (line 3) from as the node where the attack starts begins. The attacker node is a combination of the image name ("Outsideoutside") and the privilege level (ADMIN). Then, into, in a while loop (Line 4), the algorithm iterates through every node (Line 5), checks its the given node's neighbors (Line 9), and adds the edges if the conditions are satisfied (Lines 12, 16, and 26). If the neighbor was not passed, then it is added to the queue (Line 28). The algorithm terminates when the queue is empty (Line 4). Furthermore, BFS is characterized by the following properties.

Comment [Editor14]: Remark: This term is not capitalized in Algorithm 1. Please check.

- Completeness: Breadth-first Search BFS is complete, i.e., if there is a solution, Breadth-first search BFS will find it regardless of the kind of graph type.
- Termination: This follows from the monotonicity property. Monotonicity is ensured if it is assumed that an attacker will never need to relinquish a state [5, 18, 27]. In this implementation, each edge is traversed only once, making sure which ensures that monotonicity is preserved.
- Complexity: The algorithm's complexity is $O((|N| + 1) \cdot |E|)$, where $|N|$ is the number of nodes and $|E|$ is the number of edges in the attack graph.



4 EVALUATION

Real-world microservice systems ~~are composed of~~[comprise](#) many containers that run different technologies with various degrees of connectivity among each other. This raises the need for a robust and scalable attack graph generator. ~~In~~[We demonstrate use cases in](#) Subsection 4.1, ~~we show~~
~~our use cases.~~

We then ~~have a look at~~ examine how others ~~evaluate~~ have evaluated their systems. ~~Finally, in~~ In Subsection 4.2, we ~~conduct~~ discuss experiments ~~conducted~~ to test the scalability of ~~our~~ the proposed system with a different ~~number~~ numbers of containers and ~~varying degrees of~~ connectivity. ~~All of the~~ Note that all experiments were performed on an Intel(R) Core(TM) i5-7200U CPU @ 2.50GHz 50 GHz with 8GB 8 GB of RAM running Ubuntu 16.04.3 LTS.

Comment [Editor15]: Remark: Please check whether this edit retains your intended meaning. If not, please clarify.

4.1 Use Cases

Modern microservice architectures use ~~an abundance of many~~ different technologies, ~~number~~ different numbers of containers, various ~~degrees of~~ connectivity, and ~~number~~ have different numbers of vulnerabilities. Therefore, it is ~~of immense importance~~ critically important to ~~show~~ demonstrate that an attack graph generator works well in such heterogeneous scenarios. ~~To do this~~ Here, we tested ~~our~~ the proposed system on real and slightly modified ~~Github~~ GitHub examples ~~as described in~~ (Table 1-). We ~~intended to find and~~ employed test examples that are publicly available ~~for possible to facilitate potential~~ future comparison characterized by different system properties (e.g., topologies, technologies, and vulnerabilities) and ~~coming from~~ different usage domains. We also had to ~~take into account~~ consider the fact that an overwhelming majority of ~~the examples~~ publicly available examples are small ~~with~~ i.e., only one or a few containers, which made ~~this search~~ finding appropriate test examples challenging. The resulting examples are as follows: NetflixOSS, ~~the~~ Atsea Sample Shop App, and ~~the~~ JavaEE demo. NetflixOSS is a microservice system provided by Netflix ~~that is composed of~~ comprising 10 containers and uses many tools ~~like~~ e.g., Spring Cloud, Netflix Ribbon, and Netflix Eureka. ~~The~~ Atsea Sample Shop App is an e-commerce sample web application ~~consisting of 4~~ comprising four containers and uses Spring Boot, React, NGINX, and PostgreSQL. ~~The~~ JavaEE demo is a sample application for browsing movies ~~that is composed of~~ comprising only two containers and uses JavaEE, React, and Tomcat EE. We ran the attack graph generator and ~~manually~~ verified the resulting attack graphs ~~of for~~ the small examples ~~manually~~ based on domain knowledge and under the assumption that the output from Clair, ~~the~~ NVD attack vectors [6], and the ~~pre-preconditions~~ and postconditions from ~~the work of~~ Aksu et al. [4] are correct. After running the ~~proposed~~ attack graph generator, the attack graphs for the Atsea Sample Shop app and ~~the~~ JavaEE demo ~~are were~~ small as expected ~~with~~ containing only a few nodes and edges. The structure of the ~~resulting~~ Netflix attack graph ~~had~~ demonstrated a nearly linear structure in which each node ~~is was~~ connected to a small number of other nodes ~~that to~~ form a chain of attacks. This linearity is ~~because due to the fact that~~ each container is connected to ~~only~~ a few other containers to reduce unnecessary communication and increase encapsulation. Therefore, based on this ~~degree of~~ connectivity, an attacker needs to perform multiple intermediate steps to reach the target container. ~~All of the~~ Note that all examples terminated, there ~~are were~~ no directed edges from containers with higher privileges to lower privileges, ~~and no duplication of nodes and no reflexive edges were observed~~, which is in line with the ~~previously mentioned~~ monotonicity property. ~~Additionally, we notice~~ e-running In addition, the run time of ~~our~~ the proposed system ~~for with each of these examples~~ example was short ~~and~~ however, additional scalability tests ~~are needed~~ The were required. Therefore, the Phpmailer and Samba system ~~is was~~ extended and ~~ed~~ as an artificial example ~~that we use and extend in the following subsection~~ to perform ~~these~~ scalability tests. This is discussed in the following subsection.

Comment [Editor16]: Remark: Please consider revising this to “non-specific.”

4.2 Scalability evaluation

Extensive study of the scalability ~~study~~ of attack graph generators is rare in the current literature, and many parameters contribute to the complexity of ~~a~~ comprehensive ~~analysis~~ ~~analyses~~. Parameters that ~~usually~~ ~~typically~~ vary in this sort of evaluation ~~are~~ include the number of nodes, their connectivity, and the number of vulnerabilities per container. ~~All, all of these components which~~ contribute to the execution time of a given algorithm. Even though the definitions of an attack graph differ, we hope to reach ~~achieve~~ a comprehensive comparison with current methods. ~~In this case~~ Here, we ~~compare our~~ compared the proposed system to existing work in computer networks by treating ~~every~~ each container as a host machine, and any physical connection between two machines as a connection between two containers. In the following, we first ~~look at~~ examine three ~~works~~ and their scalability evaluation results. ~~After this comparison, we~~ We then present the scalability results of ~~our~~ the proposed system.

Comment [Editor17]: Remark: Please consider revising this to “methods.”

Sheyner et al. [31] ~~test~~ tested their system ~~in~~ using both small and extended examples. The attack graph in the larger example has 5948 nodes and 68364 edges. The time ~~needed~~ required for NuSMV to execute this configuration ~~is 2 was two hours~~ but, however, the model checking ~~part~~ component took ~~4~~ four minutes. The authors claim that the performance bottleneck ~~is inside~~ resides in the graph generation procedure. Ingols et al. [18] tested their system on a network of 250 hosts. They ~~afterward~~ continued the study on a simulated network ~~of with~~ 50000 hosts in under ~~4~~ four minutes. Although ~~this~~ their method yields better performance than the ~~forementioned~~ approach, ~~this, their~~ evaluation is ~~was~~ based on the ~~Multiple-Prerequisite~~ a MP graph, which ~~is different~~ differs from ~~ours~~ our target graph. In addition to this, missing an explanation of how the hosts are connected, does not make it directly comparable to our method. Ou et al. [27] ~~provide some~~ provided a more extended ~~extensive~~ study where, wherein they ~~test~~ tested their ~~s~~ MuIVAL ~~on~~ using more examples. They ~~mention~~ state that the asymptotic CPU time ~~is~~ was between $O(n^2)$ and $O(n^3)$, where n is the number of nodes (hosts). ~~The performance of the system for~~ With 1000 fully ~~connected~~ nodes ~~takes, their system~~ required more than 1000 seconds to execute.

Comment [Editor18]: Remark: Please clarify what this is. Are you referring to the method proposed by Sheyner et al.? If so, please consider stating this.

Comment [Editor19]: Remark: Please consider naming the “aforementioned approach” for clarity.

Comment [Editor20]: Remark: This text is unclear. Please clarify.

~~In our scalability experiments, we use~~ We used Samba [2] and Phpmailer [1] containers. ~~in our scalability experiments~~. We extended this example and artificially created fully ~~connected~~ connected topologies of 20, 50, 100, 500, and 1000 Samba containers to test the scalability of the proposed system. ~~The As reported by Clair, the~~ As reported by Clair, the Phpmailer container has 181 vulnerabilities, ~~while and~~ and the Samba container has 367 vulnerabilities ~~reported by Clair~~. In our tests, we ~~measure~~ measured the total execution time ~~as well as and~~ partial times: Topology, i.e., topology parsing time, Vulnerability preprocessing time, and Breath-first Search BFS time. The total time contains ~~the~~ topology parsing, ~~the~~ attack graph generation, and ~~some minor utility processes~~. ~~The Topology, Here, the topology parsing time is the time required to generate the graph topology. The Vulnerability, the vulnerability preprocessing time is the time needed required to convert the vulnerabilities into sets of pre-preconditions and postconditions. The Breath-first Search, and the BFS time is the time needed required for Breadth-first Search the BFS algorithm to traverse the topology and generate the attack graph after the previous steps are done complete. All of the components are were executed five times for each of the examples example, and their final time is was averaged. The Note that the times are given in seconds. However, the total time does not include the Clair vulnerability analysis by Clair. Evaluation of Clair is not in because~~ evaluation is beyond the scope of this analysis.

Comment [Editor21]: Remark: This text is unclear. Please clarify.

Comment [Editor22]: Remark: Please verify our edit here.

Comment [Editor23]: Remark: Please specify where this has been mentioned.

Table 2 shows the experimental ~~results of our experiments~~. In each ~~of these experiments~~ experiment, the number of Phpmailer containers ~~stays~~ was constant, ~~while~~ In contrast, the number of Samba containers ~~is increasing~~. ~~This increase is done~~ increased in a fully ~~connected~~ connected fashion ~~manner~~, where a node of each container ~~is~~ was connected to ~~every~~ all other ~~container~~ containers. In addition, there ~~are~~ were also two additional artificial containers: i.e., "outside" ~~that, which~~ represents the environment from where the attacker can attack, and the "docker host".

i.e., the Docker daemon where ~~the~~ containers are hosted. ~~Therefore~~ Thus, the total number of nodes in the topology graph is the sum of: "outside", "docker host", the number of Phpmailer containers, and the number of Samba containers.

Comment [Editor24]: Remark: Please check whether this edit retains your intended meaning.

Name	Description	Technology Stack	No.	No. vuln.	Github GitHub link
				Con- tainers	
Netflix OSS	Combination of containers provided by Netflix.	Spring Cloud, Netflix Ribbon, Spring Cloud Netflix, Netflix's Eureka	10	4111	https://github.com/Oreste-Luci/netflix-oss-example
Atsea Sample Shop App	An example online store application.	Spring Boot, React, NGINX, PostgreSQL	4	120	https://github.com/dockersamples/atsea-sample-shop-app
JavaEE demo	An application for browsing movies along with other related functions.	Java EE application, Tomcat EE	2	149	https://github.com/dockersamples/javaee-demo
PHPMailer and Samba	An artificial example created from two separate containers. We use an augmented version for the scalability tests.	PHPMailer(email creation and transfer class for PHP), Samba_(SMB/CIFS networking protocol)	2	548	https://github.com/opsxcq/exploit-CVE-2016-10033 https://github.com/opsxcq/exploit-CVE-2017-7494

Table 1: Microservice architecture examples analyzed by ~~the~~ proposed attack graph generator

Statistics	example_20	example_50	example_100	example_500	example_1000
No. of Phpmailer containers	1	1	1	1	1
No. of Samba Samba containers	20	50	100	500	1000
No. of nodes in topology	23	53	103	503	1003
No. of edges in topology	253	1378	5253	126253	502503
No. nodes in attack graph	43	103	203	1003	2003
No. edges in attack graph	863	5153	20303	501503	2003003
Topology parsing time	0.02879	0.0563	0.1241	0.7184	2.3664
Vulnerability preprocessing time	0.5377	0.9128	1.6648	6.9961	15.0639
Breadth-First Search BFS time	0.2763	1.6524	6.5527	165.3634	767.5539
Total time	0.8429	2.6216	8.3417	173.0781	784.9843

Table 2: Scalability results with ~~the~~ graph characteristics and execution times ~~in seconds.~~ [\(s\)](#)

Comment [Editor25]: Remark: Table titles are typically positioned above tables. Please check this here and at all such instances.

Comment [Editor26]: Remark: Please verify our edit here.

~~of Samba containers.~~ The number of edges ~~of in~~ the topology graph is a combination of one edge ("outside"- "Phpmailer"), n edges ("docker host" to all ~~of the~~ containers)), and $n*(n+1)/2$ edges ~~of between~~ ~~Ph-pmailer~~the Phpmailer and Samba containers. For example_20, the number of containers is 23 (one Phpmailer ~~container~~, one "outside"~~,~~ container, one "docker host" ~~container~~, and 20 Samba containers)). ~~Thus~~, the number of edges in ~~the this~~ topology graph ~~would be is~~ 253: ~~i.e.~~, one outside edge, 21 Docker host edges (one toward Phpmailer and 20 toward the Samba containers)), and 231 between-container edges (~~i.e.~~, $21*22/2=231$).

Throughout the experiments, ~~for the smaller configurations, the biggest~~the greatest time bottleneck ~~is was~~ the preprocessing step ~~for the smaller configurations~~. However, ~~this step increases~~ linearly because the container files are analyzed only once by Clair. ~~The Note that the attack graph generation time for the smaller examples is was~~ considerably less than the preprocessing time. ~~Starting from~~For example_500, we ~~can notice~~note a sharp increase in execution time ~~to (165 seconds. For)~~ compared to the previous example ~~with (i.e., example_100), where~~ the attack graph was generated in 6.5 seconds.

The total time of the attack graph generation procedure for 1000 fully-connected hosts (784 seconds) ~~outperforms was better than the~~ results from ~~Our Ou~~of Ou et al. [27], i.e., 1000 seconds. In ~~the~~ Sheyners's extended example(4 (four hosts, 8eight atomic attacks, and multiple vulnerabilities)), the attack graph took 2two hours to create. ~~Our attack graph procedure~~In contrast, even for ~~the bigger a~~ greater number of hosts (1000)~~shows~~, the proposed attack graph procedure demonstrates faster attack graph generation time. ~~It, however,~~However, the proposed system performs worse than the generator ~~from proposed by~~ Ingols et al., but that is attributed to the usage of ~~the~~ MP attack graph, which ~~is different~~differs from ~~ours~~our target graph.

In summary, we found ~~out~~that ~~our~~the proposed algorithm generates attack graphs efficiently, ~~i.e.,~~ it handles a system with ~~a thousand~~ container1000 containers in 13 minutes. Considering the strongly-connected system ~~employed~~ in the experiment; and the high number of vulnerabilities in ~~it this system~~, we ~~think~~consider that the results ~~of this experiment show~~demonstrate that the proposed system is a practical solution that can be used as part of the continuous delivery ~~proeess~~processes of real-world systems.

5 RELATED WORK


Previous ~~work has dealt with~~studies have examined attack graph generation, ~~mainly in~~primarily relative to computer networks [18, 27, 30, 31], where multiple machines are connected to each other and the Internet. One ~~early study~~of ~~the earlier works in~~ attack graph generation was ~~done~~conducted by Sheyner et al. ~~by using~~ model checkers ~~with the goal property~~ [31]. Model checkers use computational logic to ~~check~~determine if a model is correct, ~~and~~ otherwise, ~~they~~if the model is incorrect, the ~~checkers~~ provide a counterexample. A collection of these counterexamples

Comment [Editor27]: Remark: Do you mean the time cost/complexity increases? Please clarify.

Comment [Editor28]: Remark: We have edited this text to improve clarity/readability. Check whether your intended meaning is conveyed.

Comment [Editor29]: Remark: Please clarify what you are referring to.

Comment [Editor30]: Remark: Check whether your intended meaning is conveyed.

form an attack graph. ~~They state~~Sheyner et al. stated that model checkers satisfy a ~~mono-tonicity~~monotonicity property to ensure termination. However, model checkers have a computational disadvantage. Amman et al. ~~extend~~extended this work with some simplifications and more efficient storage [30]. Ou et al. ~~use~~used a logical attack graph [27] and Ingols et al. ~~et al.~~ [18] ~~et al.~~ ~~use~~used a Breadth-first-searchBFS algorithm ~~in order~~to tackle the scalability issue. Ingols et al. ~~disuss~~discussed the redundancy ~~Full of full~~ and ~~Predictive-predictive~~ graphs and ~~model~~modeled an attack graph as an MP graph with ~~content-less~~contentless edges and ~~3~~three node types ~~of nodes~~. They ~~use~~ ~~Breath-first search~~used a BFS technique to generate the attack graph. This approach provides faster results ~~in-comparison~~compared to using model checkers. ~~An~~For example, ~~with this method, an~~ MP graph ~~of~~with 8901 nodes and 23315 edges ~~is~~was constructed in 0.5 seconds. ~~Aksu et al. build~~built a method on top of Ingols's system and ~~evaluate~~evaluated a set of ~~rule pre- and postconditions~~ ~~in~~precondition and postcondition rules when generating attacks. They ~~define~~defined a specific test of ~~pre~~ dition and postcondition rules and ~~test~~tested their correctness. ~~In their evaluation, Note that~~ they ~~use~~used a machine learning approach ~~in their evaluation~~ [4].

Comment [Editor31]: Remark: Do you refer to the monotonicity property? Indefinite article “a” infers multiple properties.

Comment [Editor32]: Remark: Check whether your intended meaning is conveyed.

Comment [Editor33]: Remark: Check whether your intended meaning is conveyed.

~~Containers~~Despite their increasing popularity, ~~containers~~ and microservice architectures, ~~despite their evergrowing popularity,~~ have ~~shown~~demonstrated somewhat bigger security risks, ~~mostly because of~~primarily due to their ~~need of~~connectivity requirements and a lesser degree of encapsulation [11, 13]. To the best of our knowledge, no previous ~~work that~~study has been ~~done in the area of~~conducted relative to attack graph generation for Docker containers. Similar to computer networks, microservice architectures have a container topology and tools for ~~container~~analysis ~~of containers~~. Containers in our model correspond to hosts, and a connection between hosts translates to communication between containers.

Comment [Editor34]: Remark: Please complete the comparison here. In addition, “size” is an inappropriate way to represent security concepts. Please consider revising this to severe, serious, harmful, etc.

In summary, our contribution is ~~proposing~~using attack graph generation as part of ~~the~~DevOps practices, and providing ~~a tool~~support for this ~~idea concept~~. To that end, we ~~have~~ extended the work ~~from~~of Ingols [18] and Aksu [4] in conjunction with ~~the~~Clair OS to generate attack graphs for microservice architectures.

6 CONCLUSIONS AND FUTURE WORK

Microservices are a promising architectural style that ~~advocate~~encourage practitioners to build systems as a group of small connected services. Although ~~this style enables~~such architectures can realize better scalability and faster deployment, ~~the~~full container-based automation ~~within this style~~raises many security concerns. In this paper, we ~~have~~ proposed ~~to the use of~~automated attack graph generation ~~as part of relative to the praetices~~development of ~~developing~~ microservice-based architectures. Attack graphs ~~aid the help~~ developers ~~in identifying~~identify attack paths that ~~consist of multiple vulnerability exploitation in the~~comprise exploitable vulnerabilities in deployed services. ~~The manual~~Manual construction of attack graphs is an error-prone, resource consuming activity. ~~Hence, therefore,~~ automating this process ~~does not only guarantee~~guarantees efficient construction ~~but also~~and complies with the spirit of DevOps practices. ~~We have shown that such automation. By~~ extending previous ~~works~~work in ~~the field of~~computer networks ~~field,~~ we have demonstrated that such automation is efficient and scales to ~~large and~~complex ~~and big~~microservice-based systems.

As ~~a~~ⁱⁿ future ~~work~~, we plan to extend this work to support more frameworks ~~that are~~ used in ~~microservices~~^{microservice} systems. We also plan to study ~~the~~ possible analysis of the resulting attack graphs for ~~purposes of use in~~ attack detection, and post-postmortem forensics investigations.

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Comment [Editor35]: Remark: We have checked your references for consistency and found that there were a few incomplete references. Please check and format your references as per your target journal guidelines.

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