Towards Least Privilege Containers with Cimplifier

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Abstract
Application containers, such as Docker containers, have recently gained popularity as a solution for agile and seamless deployment of applications. These light-weight virtualization environments run applications that are packed together with their resources and configuration information, and thus can be deployed across various software platforms. However, these software ecosystems are not conducive to the true and tried security principles of privilege separation (PS) and principle of least privilege (PLP). We propose algorithms and a tool Cimplifier, which address these concerns in the context of containers. Specifically, given a container our tool partitions them into simpler containers, which are only provided enough resources to perform their functionality. As part our solution, we develop techniques for analyzing resource usage, for performing partitioning, and gluing the containers together to preserve functionality. Our evaluation on real-world containers demonstrates that Cimplifier can preserve the original functionality, leads to reduction in image size of 58-95%, and processes even large containers in under thirty seconds.

1 Introduction
In the past few years, the information technology (IT) industry has adopted containers for addressing issues related to agile deployment of software. Containers are light-weight virtualization environments to “contain” applications and provide desirable properties, such as an application-specific configuration, isolation, and resource provisioning. With recent projects, such as Docker [15], containers have become the holy grail for devops: an easy and widely-supported specification of an application and its environment that can be deployed across various software platforms. Indeed, surveys and analytics indicate undeniably high rates of Docker adoption [36, 13].

As the industry begins to adopt containers as the mechanism for deploying complex applications, techniques to secure and harden these applications must be developed. One traditional principle in security is that of principle of least privilege (PLP) [35, 22], which dictates that any module (an application, process, etc.) should be allowed only privileges that are necessary to perform its functionality. However, the current container ecosystem does not promote this important security tenet of PLP. While an application inside a container can access resources only within the container only, a container typically builds on other images, which still includes all sorts of utilities, programs, and files that may not be required by the application's functionality. These redundant resources are available to the application and in an event of a compromise only serve to increase the possibility of further harm. Frequently, a container packs a complex application consisting of multiple application components, which goes against the principle of privilege separation (PS) [31]: separating modules with different privileges so that a compromise of one module limits the attacker to only a subset of privileges. PLP and PS dictate that a container should run only one simple application and should pack only as much resources as needed to fulfill its functionality requirement.

For example, consider a wiki installation, which runs a web server and stores the documents in a database server. If both the web server and the database server have free access to each other’s resources, a compromise of one component could escalate to the compromise of the other. Furthermore, if the database server does not need netcat for its operations, then netcat should not be available to the database server. The wiki example is further elaborated in Section 2.2 and will serve as the running example for our paper.

This paper presents the design and implementation of Cimplifier (pronounced simplifier) to address these problems. Given a container, we first use dynamic analysis to understand how resources are used. We
then partition the container based on very intuitive and simple user-defined policies into multiple containers, each running one or more application components at the granularity of individual executables (i.e., currently, we do not partition an executable), and pack just the resources needed to execute these components. Finally, we provide techniques for an application component residing in one container to be able to invoke another component residing in another container, so that together these containers provide the same functionality as the original container. CIMPLIFIER does not need application source code nor does it depend on applications using a particular language or runtime stack (e.g., Java VM) and hence can handle a wide class of containers. Our work resembles existing work on classic privilege separation \[9, 14\]. However, our target context (i.e., containers) poses unique opportunities and challenges, which makes our work significantly different from the above-mentioned existing work. We elaborate on these differences in our section on related work.

We evaluated our CIMPLIFIER prototype on several real-world containers, ranging from simple web servers and database engines to complex applications like a wiki, a blogging engine, and a log-analysis stack. Our evaluation demonstrates that CIMPLIFIER is effective in creating functional partitions guided by simple and intuitive user-defined policies and reducing container size by 58–95%. Our tool also has low execution overhead (e.g., on our largest example it runs in under thirty seconds.)

Our contributions can be summarized as follows:

- **Resource identification.** We develop techniques based on system call logs to analyze the usage of resources and associate them with various executables in the application container being analyzed.

- **Container partitioning.** We devise an algorithm for partitioning a container (based on a simple user-defined policy) and for associating resources with the components of a partition.

- **Remote process execution.** We introduce remote process execution (RPE) as a mechanism for gluing components. Our mechanism allows a process running in one container to transparently execute a program in another container without relaxing the separation boundaries provided by containers.

- **System prototype.** We implemented the above techniques in a prototype implementation called CIMPLIFIER, which is an end-to-end system for container partitioning and resource slimming. Our tool takes as input a container, system call logs, and a user policy and outputs partitioned containers, each packing only resources needed for functionality.

The rest of this paper is organized as follows: Section 2 provides the requisite background, problem definition, and an overview of our approach. Our methodology is discussed in Section 3. We present evaluation results in Section 4. Related work is discussed in Section 5, followed by a discussion on limitations and future work in Section 6. We conclude in Section 7.

2 Overview

This section provides the relevant background, the problem statement, and issues specific to the container ecosystem. We also provide a brief overview of our solution.

2.1 Background

Containers are potentially-isolated *user-space instances* that share the same kernel. Mechanisms exist in several operating systems for providing multiple isolated user-space instances. Solaris Zones and FreeBSD Jails are some well-known examples. The Linux kernel implements *namespaces* to provide user-space instantiations.

A namespace is an abstraction around a global resource giving the processes within the namespace an illusion of having an isolated instance of the resource, i.e., any operations on the resource are visible to the processes within the namespace only. Six kinds of namespaces are defined in Linux: IPC (inter-process communication), network, mount, PID (process identifier), user, and UTS (UTS stands for Unix timesharing system and the namespace allows for separation of hostnames, for example). Processes with appropriate Linux capabilities\(^1\) can spawn new namespaces through the *clone* or *unshare* system calls.

Container implementations on Linux, such as LXC \[24\] and Docker, employ the namespaces feature to provide a self-contained isolated environment. This isolation is based on the fact that resources that do
not have a name in a namespace cannot be accessed from within that namespace. For example, a process outside a given PID namespace cannot be specified by a PID in that namespace. In addition, container implementations use *cgroups*, another Linux kernel feature allowing for resource limiting, prioritization, and accounting. Together cgroups and namespace provide mechanisms to build container security (cgroups provides protection against denial-of-service (DOS) while namespace isolation provides basic sandboxing). Finally, Linux capabilities and mandatory access control (MAC) systems, such as SELinux or AppArmor, are often used to harden the basic namespace-based sandboxing [17].

Besides the implementation of a container itself using primitives provided by the kernel, projects such as Docker and the Open Container Project also made strides in developing specifications and tools for implementing and deploying containers. For example, the files necessary for running applications (the application code, libraries, operating system middleware services, and resources) packed in one or more archives together with the necessary metadata constitute a *container image*. The image metadata includes various configuration parameters, such as environment variables, to be supplied to a running container, and network ports that should be exposed to the host.

Systems like Docker are designed particularly with the idea of deploying applications and hence are meant to run *application containers* as opposed to *OS containers*. That is, they offer mechanisms more suited to run simple applications (such as a HTTP server) rather than a full operating system with a slew of services and processes. In this regard, a container may be viewed as an application packed together with all the necessary resources (such as files) executing in an appropriate environment. The focus of this work is such application containers, henceforth referred to as simply *containers*, and we demonstrate our methodology in the context of Docker and its ecosystem, although our techniques are applicable in other contexts.

### 2.2 Problem Statement

As mentioned earlier, an application container packs a given application together with its resources and configuration so that the application can execute independently on a host as an atomic unit. Based on the principle of least privilege, an ideal container should satisfy two requirements: (A): Slim it should pack no more resources than what its functionality needs, (B): Separation it should execute only one simple application. Requirement A is motivated by reducing the attack surface and requirement B is motivated by ease of hardening (simple applications are easy to harden using systems such as SELinux and AppArmor). Moreover, a simple application is also more auditable (e.g., using existing static-analysis tools, such as Coverity and Fortify) than a complex one. Furthermore, running one simple application per container aligns with the microservices philosophy whereby complex applications are composed of independently running simple applications that are easier to manage and deploy.

These requirements mandate that complex application containers be decomposed or partitioned into minimal simple containers. This paper is a step towards automatically performing this task. Next, we provide a running example, which will be used at various points in the paper, and then state a general form of the container partitioning problem.
Running example. We consider a popular container from the Docker Hub (the official repository for container images) called appcontainers/mediawiki. As the name suggests, this container provides, MediaWiki, a popular wiki application [25]. The container may be used in different modes; we will discuss only the stand alone mode, which allows running the entire application from just this container. The container image has Apache HTTPD and MySQL server installed. At startup, it performs configuration to set up the MediaWiki PHP source code for use with HTTPD, set up a TLS certificate using OpenSSL for serving HTTPS connections, and start and configure MySQL and HTTPD servers.

Since HTTPD and MySQL server are separate entities, and so to maximize isolation between them, we would like them to execute in different containers. The MediaWiki PHP code also spawns ImageMagick to convert uploaded images to different sizes. Since uploaded images may be maliciously crafted, we would like to separate their processing by ImageMagick from the rest of the application, i.e., ImageMagick should run in a separate container. The transformation we would like to achieve is depicted at the right of Figure 1.

Container partitioning problem. A container $C$ is a set of executables $E = \{e_1, \cdots, e_n\}$. Let $\mathcal{R}(C)$ be the set of resources used by the container $C$ (the resources could be files, socket objects, etc.). Moreover, there are two kinds of user constraints positive and negative (the positive constraints $UC_+ \subseteq E \times E$ and the negative constraints $UC_- \subseteq E \times E$). Intuitively, if $(e_i, e_j) \in UC_+$, then executables $e_i$ and $e_j$ should be put in the same container. Similarly, if $(e_i, e_j) \in UC_-$, then executables $e_i$ and $e_j$ should be not be put in the same container.

Now the container partitioning problem can be defined as follows: Given a container $C$, $UC_+$ and $UC_-$, find a set of containers $\{C_1, \cdots, C_k\}$ (where $C_i \subseteq E$, $C_i \cap C_j = \emptyset$ if $i \neq j$, and $\bigcup_{i=1}^k C_i = E$ (or in other words $\{C_1, \cdots, C_k\}$ is a partition of $E$).

The set of resources needed by a container $C_i$ (denoted by $\mathcal{R}(C_i)$) is implicitly defined. Note that additional constraints (e.g. minimizing the number and size of the containers) can be easily added to the problem definition. Our solution strategy takes into account these additional constraints. For example, one constraint might be to find a partition $\{C_1, \cdots, C_k\}$ that minimizes $\max\{|\mathcal{R}(C_1)|, \cdots, |\mathcal{R}(C_k)|\}$. To perform the original functionality, the containers in $\{C_1, \cdots, C_k\}$ must cooperate with each other, such as through network or inter-process communication or even shared, regular files.

The above problem entails reducing the set of required resources. In fact, a good algorithm will attempt to minimize the resource set of each container so that the container does not have any redundant or unused resources. Such containers are referred to as slim containers. In the Docker ecosystem, it is common to have simple images built on top of “fat” operating system images (Docker has a concept of layered images, where a container image can be defined by a few changes over another image), so that running even a simple application container may take hundreds or thousands of megabytes of disk space. For example, the official Python image, which one might consider as the base for a simple Python application, is over 675 MB! Needless to say, much of the file content in this image is never used. With such huge image sizes being a rule rather than an exception in the Docker ecosystem, numerous articles and blog posts have been written about slim containers [14, 19, 39]. Our algorithm tries to reduce the size of the resources associated with a container $C_i$, i.e., we achieve slimming automatically.

Other benefits. We also see new opportunities in a good solution for container partitioning. First, it may enable an altogether new workflow, whereby a system administrator starts off by installing applications in one monolithic container, as is done in a traditional operating system, and then reap benefits of automatic container partitioning. In such a workflow, the system administrator need not be concerned about how different application components need to connect with each other (as she would be when manually preparing containers for each of them). Second, container partitioning could be an enabling precursor to automatic multi-location deployment of complex applications: partitions of containers could be distributed across multiple locations (physical servers or geographic locations). This could be done for reasons like load balancing or privacy compliance (such as, certain data resources should remain within an enterprise or be encrypted).

2.3 Our Approach

Given a container, our work partitions it at the level of application executables so that an executable binary is one atomic unit that can be placed in a partition. Partitioning at granularities finer than executables is
Figure 2: Architecture overview. We analyze system calls from model runs of the input container to identify resources. The application together with these resources is then partitioned across several containers guided by a user-defined policy. These containers function together through remote process execution, which acts as a glue among them.

not within the scope of the current work but may be achieved by combining our work with previous work on program partitioning and privilege separation [6, 10, 8].

Container partitioning poses three technical challenges (A) How do we identify which resources are necessary for a container? (B) How do we determine container partitions and associate resources with them? (C) How do we glue the container partitions so that together they provide the same functionality as the original container?

Our approach utilizes dynamic analysis to gather information about the containerized application’s behavior and functionality. We collect detailed logs from executions of a given container. We use these logs to construct resource sets for different component executables. Based on flexible, pluggable policies, container partitions are determined. The resulting containers are populated with the resources needed for correct functioning of the executables. Container mechanisms themselves provide for complete isolation among containers. Based on the resource sets identified, we relax this isolation to share some resources across containers on an as-needed basis. Finally, we introduce a new primitive called remote process execution to glue different containers. It relies on the availability of a shared kernel to allow a process to transparently execute a program in a different container. The approach is schematically depicted in Figure 2.

While our approach uses dynamic analysis, partitioning may also be possible through a static analysis. Both the approaches have their advantages and disadvantages. In dynamic analysis, resource set identification may not be accurate if code coverage during container executions is not complete. Static analysis does not suffer from this limitation but faces significant challenges in our context: in typical containers that we studied application components are written in several languages (e.g., shell script, PHP, and compiled C and C++), the application is strewn across multiple shared object libraries and executables, and the content of the environment variables and configuration files dictate an application’s runtime behavior. Our dynamic analysis on the other hand stays on the simple, well-defined system call interface and is more manageable. Solutions combining static and dynamic analyses to incorporate the advantages of both will be interesting to investigate in the future.

3 Methodology

Our algorithm has three main steps. Resource identification: In this step we identify the accesses of different files, IPC, and network objects by various processes in executions of the original container. Partitioning: This step utilizes the user policies and some other information to partition the original container into several containers. Gluing: In this step we “glue” the containers together to preserve functionality: we introduce remote process execution as the mechanism to glue containers. This section details these three steps and describes a few interesting details of our system.
3.1 Resource Identification

Resource identification is the first step in our methodology that enables association of various resources, such as file, IPC and network objects, to the subjects, i.e., the entities that act upon them. The next steps that perform the actual partitioning use this information to decide the resources associated with each container. For collecting this information, the system call interface serves our purpose well because it allows complete access to the information exchange happening between the user-space processes and the kernel. Actual resource access, management, and so on happens inside the kernel, and so a process must make system calls to the kernel to perform any action related to resources. There are several options for performing system call resource access, management, and so on happens inside the kernel, and so a process must make system calls to access to the information exchange happening between the user-space processes and the kernel. Actual

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Analyzing system call logs. Let a system call event be defined as a tuple \( E = (i, c, \rho) \), where \( i \) is the thread ID of the caller, \( c \) is the name of the system call (e.g., open or rename), \( \rho \) is a sequence of parameters to the system call (the last element of this sequence is the return value of the system call). Each system call has an associated type which determines how to interpret a parameter (e.g., whether a parameter should be interpreted as a pathname or as an integer return code). A system call log is simply a sequence of system calls and an execution log is a set of logs. Given a log \( \sigma = (E_1, E_2, \cdots, E_m) \) we define \( \Gamma_j \) as the state of the system after the sequence of system calls \( E_1, E_2, \cdots, E_j \) is executed (we assume an initial state \( \Gamma_0 \)). Note that the event \( E_k \) is executed in the state \( \Gamma_{k-1} \). Using the semantics of system calls we can define for each tuple of a system call \( E \) and state \( \Gamma \), a tuple \( (R, W) \), where \( R \) and \( W \) are resources that system call \( E \) reads from and writes to when executed in state \( \Gamma \). We call this function \( rsr \) (i.e., \( rsr(E, \Gamma) = (R, W) \)). Note that this function can be “lifted” to logs and execution logs via the standard collecting semantics. For example, for a log \( L = (E_1, E_2, \cdots, E_m) \), we have that \( rsr(L, \Gamma) \) is equal to

\[
\left( \bigcup_{E_i \in L} rsr_1(E_j, \Gamma_{j-1}), \bigcup_{E_i \in L} rsr_2(E_j, \Gamma_{j-1}) \right)
\]

In the equation given above \( \Gamma_j \) is the state reached from \( \Gamma \) after executing the sequence of system calls \( E_1, \cdots, E_j \) and \( rsr_i \); for \( i \in \{1, 2\} \) is the \( i \)-th component of the tuple. Given an execution log \( EL = \{L_1, \cdots, L_m\} \) and a state \( \Gamma \) we define \( rsr(EL, \Gamma) \) to be

\[
(\bigcup_{L \in EL} rsr_1(L, \Gamma), \bigcup_{L \in EL} rsr_2(L, \Gamma))
\]

These sets play a crucial role in deciding which resources are exclusively associated with a container and which resources are shared between containers. Next, we describe how different kinds of resources, such as files, IPC and network, are handled in the above framework.

Files. Files are handled through numerous system calls but all of them map neatly to the above abstractions. Intuitively, a file that should exist for the success of the call is placed in the read set. Creation, such as by opening a previously non-existing file or by renaming files, modification such as opening in append mode, and modification of metadata such as by using chmod all result in adding the file to the write set. Files and other resources referred to by file descriptors in the system call arguments are not added to these resource sets. The reason is that a file descriptor already had a resource associated with it when it was created and it was at the time of creation, such as through the open system call, that the resource was added to the resource set. File descriptors are capabilities and may be passed across processes. A process may be able to perform system calls on a file descriptor that was passed to it from elsewhere even if the associated resource is not directly available to it. Thus it is not necessary to make the resource available in the container running this process.

Inter-process communication. There are several inter-process communication (IPC) options available; we support an important subset of them. Any IPC that happens without naming a resource, such as that through channels created by pipe or socketpair system calls, is implicitly supported in Cimplifier. Such IPC typically depends on file descriptor inheritance, support for which is described in Section 3.3. Named pipes or FIFOs are one IPC mechanism that use named resources. Named pipes exist as file system nodes; one process opens the pipe for reading and another for writing. This establishes a communication channel
between the two processes. Since named pipes reside on the file system and are opened in the same way as regular files are, they are handled in the same way as files. Unix domain sockets are another IPC mechanism. When a process **binds** to a socket it specifies the socket address, creating a node named by that address on the file system (unless it is an abstract address). Another process may **connect** to this socket by specifying the socket address. For the success of the **bind** call, the parent directory of the socket should exist, making it a candidate to be placed in the read set. The socket address file itself is considered as being modified by both the binding and the connecting processes and is hence placed in the write set. There are other IPC mechanisms such as message queues and semaphores that we do not currently support. We have however not found them to be used in any of the containers we evaluated and hence did not face difficulties in partitioning due to this reason. Lack of some IPC mechanisms is not a fundamental limitation of our approach and can be addressed by further engineering effort.

**Network communication.** Network communication is sometimes used within a container such as by a web server to connect to a backend database server. Unlike Unix domain sockets, in the case of network sockets, the socket address is not a file node and a **bind** or **connect** call is not needed for connectionless sockets. Nonetheless, for connectionless sockets, the socket address is provided in the **recv** and **send** system calls. This socket address is placed in write set.

### 3.2 Partitioning

Let $E = \{e_1, e_2, \ldots, e_n\}$ be the set of executables in a container. On Linux, any run of an executable starts with the **execve** system call (the other **exec** family functions, and **system** and **popen** functions ultimately make this system call). Using the semantics of **execve** we can associate an executable $e_i \in E$ to each system call in the execution log (i.e., the system call originated from a function in that executable). Using this information and the result of the resource identification step, we can associate a set of resources read and written by an executable. We next describe our partitioning algorithm.

**Our partitioning algorithm.** Let $E = e_1, \ldots, e_n$ be the set of executables in a container. With each executable $e_i$ we associate a tuple $(R(e_i), W(e_i))$, where $R(e_i)$ and $W(e_i)$ are the resources read and written by $e_i$, respectively. Note that given a subset of executables $E' \subseteq E$, the tuple associated with it is $(\cup_{e \in E'} R(e), \cup_{e \in E'} W(e))$.

Let $G = (E, X)$ be a directed graph whose set of vertices is the set of executables $E$ and the set of edges $X \subseteq E \times E$ is such that $(e_i, e_j) \in X$ if $e_i$ calls $e_j$ (some function in executable $e_i$ executes $e_j$). In other words, $G$ is the call graph at the executable level. Currently, we construct $G$ dynamically by inspecting the execution logs, but it could be easily constructed statically.

Let $UC_+ \subseteq E \times E$ and $UC_- \subseteq E \times E$ be the positive and negative constraints provided by the user. For each executable $e_i$, let $C(e_i)$ be the current index of the container in the partition. Our algorithm works in two steps as follows:

**Initial partition based on user constraints:** Each executable is in a single container, i.e. $C(e_i) = i$. For each, constraint $(e_k, e_j) \in UC_+$ we merge the containers that have $e_k$ and $e_i$ (i.e., we merge the containers $C(e_i)$ and $C(e_j)$ into one container. Note that this can be performed by using a simple re-indexing). However, we do not perform a merge corresponding to a constraint in $(e_i, e_j) \in UC_-$ if it will violate any negative constraint $UC_-$ (i.e. there is $(e_i, e_j) \in UC_-$ such that $e_i$ and $e_j$ will be in the same container after the merge). We keep merging containers using this rule, until we reach a fix-point (i.e., the partition induced by $C(\cdot)$ does not change).

**Updating the partition based on the call graph:** Intuitively, if $(e_i, e_j) \in X$ (some function in $e_i$ calls a function in $e_j$), then $e_i$ and $e_j$ should be in the same partition as long as the given constraints are not violated. For each edge $(e_i, e_j) \in X$ we merge the containers $C(e_i)$ and $C(e_j)$ as long as any negative constraint in $UC_-$ is not violated. We keep merging containers based on the call graph until we reach a fix point.

In our partitioning algorithm we have experimented with three types of user defined policies, which can be easily specified using our formalism.

**All-one-context.** This policy places all executables into a single container. Thus, it does not perform any container partitioning. However, since only the resources accessed during test run are placed in the container,
this policy is tantamount to container slimming. Thus container slimming is just the simplest configuration of Cimplifier. In our formalism, this corresponds to \( UC_+ = E \times E \) and \( UC_- = \emptyset \).

**One-one-context.** This policy places each executable into a separate container so that no two executables share containers. While this policy is useful for testing Cimplifier, it is not practical for reasonably complex containers that may involve tens or even hundreds of executables. (The container of our running example uses 49 different executables, including simple utilities like cat and tail as well as related executables, which together can be considered as one component, like HTTPD. Putting each executable in a separate context is unnecessary in these cases.) This policy corresponds to \( UC_+ = \emptyset \) and \( UC_- \) contains all pairs \((e_i, e_j)\) such that \( i \neq j \).

**Disjoint-subsets-context.** In this policy, the user specifies disjoint subsets of executables, not necessarily covering all the executables. The subsets correspond to different containers. That is, a container corresponding to a given subset contains executables in that subset but in no other subset. Some executables may not have been specified and are considered don't cares; they can be placed in any container. This policy is practically useful. In our running example, one can specify the HTTPD-related executables in one subset, MySQL-related ones in another and ImageMagick-related ones in another. Other executables such as cat, mv, and chmod are small and may not be considered sensitive to warrant separate containers and hence can be placed anywhere as needed to optimize performance.

Apart from the above policies, it is possible to implement more intricate policies as well. For example, consider two programs both invoking openssl to configure cryptographic keys. If the user would prefer that the two invocations of openssl from the two programs happen in separate contexts to prevent any interference and protect cryptographic keys, it is possible to define a policy that does so. Such a policy will separate the two openssl contexts by the invoking contexts: if the context of first program invoked openssl, then run it in one container else run it in the other container. The above is an example of a policy based on execution-history [2]. Our policy language can be readily extended to support history-based policies.

**Resource placement.** To associate resources with containers (we call this resource placement), we begin with resources read by its executables. There are some tricky issues that arise here. For example, before placement, this “read” set must be extended to cover all dependencies. In particular, if a file indicated by a given path is placed in a container, we must ensure that all the directory components in the path leading up to the file are also placed in the container. In addition, while placing resources, we make sure that their metadata (such as permissions, ownership, and modification times) is preserved.

A resource may need to be placed in multiple containers. In such a case, the nature of resource access determines how the placement is performed. If a resource is read-only, the resource can be safely duplicated: each container gets its own copy of the resource. If a resource is modified or created by one of the containers, it should be shared. Docker natively provides the capability of mounting host files at given mount points inside a container. Such mounts are called volumes. Volumes may be shared between containers, i.e., one host file may be simultaneously mounted in multiple containers. For file resources as well as named pipes and Unix sockets, we use shared volumes for shared resources. Note that in case a resource is created by a container at runtime and is used by another container, the parent directory of the resource must be shared. This is because Docker volumes may only be mounted when a container is started and Linux does not allow mounting of non-existent files. Our solution does not differentiate between created files and modified files and hence, we always mount parent directories when resources are shared. Sharing parent directories can result in over-sharing of resources; this compromise appears necessary, however, as volumes appear to be the only way to share resources among containers.

For sharing network resources, we need to match socket addresses from the write set. This match is not an exact string match but made according to the socket address specification semantics. For example, the bound, listening TCP/IP address \((0.0.0.0 : 3306)\) and the connecting TCP/IP address \((127.0.0.1 : 3306)\) match. Based on such socket address matches, we determine the containers that need to communicate over the network. Since the client (connecting or sending process) may try to connect at the localhost/looback address (as it may have been configured in the original container) but now the destination address is the hostname/IP address of the other container, we need to run a port forwarder that forwards connections and messages from a localhost address to the remote container address. This has some overhead and realizing that sharing the network namespace may not introduce significant security issues, our current implementation takes the option of sharing the network namespace across the created containers.
3.3 Gluing

The remaining technical challenge in obtaining a functional partitioned containers is to “glue” them together to maintain the original functionality. Our technique to handle this challenge is remote process execution (RPE). RPE transparently allows a process to execute an executable in a container different from the one in which it resides. By transparency, we mean that neither of the two executables (caller and the callee) need to be modified or made aware of remote process execution.

Returning back to our running example, MediaWiki uses ImageMagick to create thumbnails of uploaded images. Since Mediawiki’s PHP code runs in the HTTPD container and ImageMagick, corresponding to the convert executable, runs in a separate container, simply executing convert from PHP code will fail because the executable file convert does not exist in the HTTPD container. We need a technique that allows the PHP code to execute convert and yet the actual execution of convert should happen along with its resources in the ImageMagick container. In the same running example, the need to execute processes in other containers arises elsewhere as well: the startup script invokes executables in HTTPD and MySQL containers to start the HTTPD and MySQL servers, respectively. In general, RPE serves as the fundamental glue primitive among partitioned containers and is crucial for preserving functionality.

Our solution works as follows: consider the scenario in which an executable image $I_1$ in container $C_1$ needs to execute another executable image $I_2$ that actually resides in container $C_2$. Our solution is to place a stub $I'_2$ corresponding to the actual executable $I_2$ in container $C_1$. We also run a “server” in $C_2$ to accept RPE requests. When $I_1$ executes $I_2$, it is actually $I'_2$ that is executed ($I'_2$ is on the same path as $I_2$). $I'_2$ marshalls the command arguments, its environment, and some process attributes and sends an RPE request to the server running on $C_2$, which then executes $I_2$ on behalf of $I_1$. This scenario is described in Figure 3. The concept of RPE strongly resembles remote procedure calls (RPCs) where a process invokes a stub procedure, which marshalls the arguments supplied and sends them to the remote server, which unmarshalls the arguments and calls the actual procedure with those arguments. The key difference in our context is that instead of shipping just the arguments, we also need to ship the process environment as well as low-level process attributes. Our key insight is that the local and remote processes share a kernel and thus appropriate shipping of process attributes and file descriptors can make RPE transparent to the participating programs. RPCs cannot assume a shared kernel and therefore cannot provide as rich features and transparency as we can. When the process ends, we ship the return code of the process to the executing process. In addition, we provide for asynchronous signaling (i.e., passing POSIX signals) between processes. All these aspects require a detailed understanding of the specification of a process. To highlight the difference between RPE and RPC we describe one mechanism (i.e., how attributes are replicated at start). Due to lack of space we
will not describe other details.

**Attribute replication at start.** $I_2'$ obtains the attributes to be replicated through the relevant system calls while the server side sets those attributes through another set of relevant system calls just before executing $I_2$. Some of the attributes, such as the user and group IDs, may be set only by a privileged user. Therefore, $S$ runs as root. The arguments and environment arrays are readily available to $I_2'$, and thus easily copied over, and the remote side can execute $I_2$ supplying the same arrays. The replication of file descriptors (henceforth called fds) needs further discussion. $I_2'$ may discover its open fds to be replicated by examining the entries of `/proc/self/fd` and filtering out the fds it itself opened (particularly, the one opened to read this directory and possibly also the socket fd connected to the server). Although fds are ints, they have a special meaning associated to them by the kernel and thus have to be transferred to other processes using the functionality provided by the kernel (this highlights one of the key differences with RPC).

One common method of transferring fds is through ancillary messages feature of Unix domain sockets, which is why our client and server use these sockets. At the server side, the received fds may not have the same number as the originals. For example, the fd 2 may have been received as fd 4. This final conversion of a descriptor to the right number can be done by using `dup2` system call and then calling `close` on the original descriptor. Thus, we have made sure that if $I_2$ expects an open fd 3, for example, from $I_1$, it will receive that same fd number even when executing remotely. Some readers might legitimately wonder why replication of file descriptors is necessary. The answer is that file descriptor inheritance is behind the functioning of numerous mundane tasks. An example will make this clear: upon executing “`cmd > file1`” in a shell, the shell creates a new process (by `fork`, for example); opens `file1` and duplicates (using `dup2`) the newly opened file descriptor to fd 1 (corresponding to stdout) and then executes `cmd1`. A similar creation of file descriptors and duplication happens for piping output, as in “`cmd1 | cmd2`”. This makes replication of file descriptors crucial for transparent execution.

**Generalizations.** It is worth noting that the concept of remote process execution as described above is actually independent of containers but we do need a shared kernel because of the need to replicate file descriptors. Thus, the technique could be applied to other applications where an unprivileged or sandboxed application should execute a process in another sandbox, for example a SELinux sandbox [42]. It is also worth noting that the techniques described above are not specific to Linux also. Even though our implementation uses Linux-specific API and constructs for concreteness, it is possible to make it portable across most of the modern Unix platforms. Thus our RPE mechanism should also be applicable to container mechanisms on other operating systems, such as FreeBSD Jails or Solaris Zones.

### 3.4 Implementation

We have implemented a prototype of Cimplifier. Our implementation consists of about 2,000 lines of Python and C code, with C being used to implement RPE.

Our resource identification relies on system call logs, which can be collected in several ways, such as by hooking `libc` functions that wrap system calls by techniques like `LD_PRELOAD`; by using the `ptrace` system call, which allows a tracer process to collect information from and control a tracee process; by using in-kernel information collection modules, such as SystemTap [38] or SysDig [37]; or by using Red Hat’s Audit system [34]. Each has their advantages and disadvantages; we used `ptrace`. Specifically, we use the `strace` utility, which uses `ptrace` and is meant for system call logging.

Our prototype makes a few deviations from the resource identification semantics described earlier. One particularly interesting case is that of unsuccessful system calls. The system calls may fail for variety of reasons and finding the exact reason for failure requires emulating the relevant kernel code in its entirety (note that `errno` gives only a broad reason for failure). In our prototype implementation, for most part, we ignore unsuccessful system calls as if they never happened. If a program interprets the reason (through `errno`, for example) for a failed system call, we may not be able to capture this behavior. For remote process execution, we do not currently replicate some less commonly used attributes. For example, we do not replicate nice value and resource limits. For the containers we have studied, such attributes remain at default value across the container boundaries, so our experiments are not affected. A production deployment
however would need to perform a complete replication, especially given that it is relatively straightforward to implement these features.

4 Evaluation

This section presents our experiments to evaluate CIMPLIFIER and the results thereof. Our evaluation seeks to answer the following questions.

- Does CIMPLIFIER work on real-world containers and do its output containers preserve the functionality of the input containers?
- How effective is CIMPLIFIER at partitioning real-world containers and eliminating redundant resources from them?
- How much time does CIMPLIFIER take to analyze the inputs and produce the outputs?
- What is the runtime overhead of the output container system produced by CIMPLIFIER?

Our experiments are divided into two parts: experience with real-world, popular containers and a microbenchmark to measure runtime performance. We summarize the findings from our experiments and then describe the latter in detail.

- CIMPLIFIER succeeded in processing all containers we experimented on. Furthermore, the resultant containers preserve the functionality that the input containers were tested for.
- CIMPLIFIER produced the desired partitions as specified by the user constraints. As for redundant resource elimination, CIMPLIFIER reduces container sizes by 58-95% in our experiments.
- Given input containers, their system call logs, and partitioning policies, CIMPLIFIER produces output containers in under 30 seconds for even the most complex containers we examined. It is thus fast enough for real-world use to partition and slim containers.
- The partitioned containers did not incur any observable runtime overhead. Overhead is expected only in our glue (remote process execution), which we measure to be 1-4 ms on realistic programs and is amortized to negligibility over the entire runs of the programs.

4.1 Case Studies

We tested CIMPLIFIER on seven popular containers from Docker Hub. Four of these containers were chosen from the Docker official images (the Docker project directly provides and maintains about a hundred so-called official container images providing popular applications), which are simple but highly used containers. As each of these run one simple application only, we did not expect CIMPLIFIER to partition them but only to perform slimming in accordance with least privilege. The other three containers are popular community-contributed containers and run multiple application components that should be partitioned. We used the latest versions of these containers, as collected in January-February 2016.

Our system call logs are collected from test runs that exercise the given container’s functionality. In a workflow using CIMPLIFIER in practice, a system administrator would have a specific purpose in deploying an application and would therefore provide test runs demonstrating that one purpose only. Therefore, where multiple configurations are possible, we exercise our containers based on the functionality we want from them. A preprocessing run through system call logs shows the executables used in the container; we use this output to write our partitioning policies.

The rest of this subsection will examine each container as a case study and then present a discussion highlighting noteworthy lessons. Owing to space limitations, we only discuss the most relevant or interesting details and provide a summary of the results in Table[1]. All the experiments were conducted on a VirtualBox virtual machine running Fedora 23 and configured with a single CPU core and 2GB of memory. The base hardware was a 2013 MacBook Pro with 2.3 GHz Intel Core i7-4850HQ CPU and a solid state drive.
Table 1: Containers studied. Each row specifies the container identifier on Docker Hub, the number of downloads (an indicator of popularity), the container image size, the time Cimplifier took for analysis, the combined size of all output containers, and the percentage reduction in the size. The first four containers are simple and hence not partitioned but only slimmed. The containers (or container systems) produced by Cimplifier are functionally identical to the original containers.

| Container                        | # Downloads | Size  | Analysis time | Result size | Size reduction |
|----------------------------------|-------------|-------|---------------|-------------|----------------|
| nginx                            | 24 M        | 133 MB| 5.5 s         | 6 MB        | 95%            |
| redis                            | 18 M        | 151 MB| 5.5 s         | 12 MB       | 92%            |
| mongo                            | 7 M         | 317 MB| 14.0 s        | 46 MB       | 85%            |
| python                           | 3 M         | 119 MB| 5.3 s         | 30 MB       | 75%            |
| appcontainers/mmediawiki         | 178 K       | 576 MB| 16.8 s        | 244 MB      | 58%            |
| eugeneware/docker-wordpress-nginx| 26 K        | 602 MB| 16.2 s        | 201 MB      | 67%            |
| sebp/elk                         | 59 K        | 985 MB| 26.1 s        | 236 MB      | 76%            |

Nginx. Nginx [29] is a high-performance, popular web server. We chose to use our Nginx container as a static website server and ran tests in this configuration. Our test runs for collecting system call logs consisted of requesting both existing and non-existing website content through a web browser. The call logs include only the nginx executable and there is no expectation of partitioning. The website root itself exists on an external volume and files from it are not removed (this allows the new container to serve even files that were not served in the test runs). Cimplifier reduced the size of this container by 95% while keeping it functional. The reduced container does not have a shell or any of the common Unix utilities, which helps in mitigating further exploitation in the event of a compromise.

Redis. Redis [33] is an in-memory data structure store that find applications as a cache, message broker, and so on. Our tests to exercise this container consisted of running the redis-benchmark utility with the container configured in append-only persistence mode (in this mode, Redis logs each operation it executes to a file). The utility sends various commands to the Redis server, testing all Redis operations. Cimplifier slimmed the container to just 8% of the original while preserving functionality.

MongoDB. MongoDB [26] is a NoSQL database engine. The container runs mongod, the MongoDB server. Our test runs included test cases to exercise the core functionality of mongod. In particular, we used jstests/core integration tests from MongoDB source repository. 45 of 825 tests failed on the original container for unknown reasons and so were excluded from test runs. Cimplifier was able to process the container and the logs in 14 seconds to produce a functionality-preserving container slimmed to just 15% of the original.

Python. Our next container provides the Python runtime. We use this container as a base for a simple Python web runtime container, which we slim with Cimplifier. Slimming should remove even files from the Python runtime and libraries if they are not needed to run the application. To find our candidate web application, we explored the list of websites powered by Flask, a popular Python web application framework (the list is curated by the Flask project), and selected the list’s first open-source website, which was also functional on the Web. We thus selected www.brightonpy.org the website of a Python user group. Our test runs included setting up the website container and opening web pages in a browser. Cimplifier could process the resulting logs to produce a container that served the website identically while reducing the container size from 119 MB (this includes the files added to the Python container to setup the web application) to 30 MB. We would also like to note that our Python container is different from other containers we experimented on as it builds on Alpine, a Linux distribution with a focus on space efficiency (the other containers build on more mainstream distributions like Debian and CentOS). Alpine-based official images are a recent effort of Docker to reduce image sizes [11] (most official images do not have Alpine variants yet). This particular case study shows that Cimplifier can eliminate resources even from an already space-efficient container.

Having discussed single-application containers, we now switch to containers that run a full stack of applications, which should be partitioned.
Mediawiki. This study considers appcontainers/mediawiki, the container of our running example. As shown in Figure 1, we would like to split this container into separate Apache HTTPD, MySQL, and ImageMagick partitions as well as an initial configuration partition (a separate partition for initial configuration is not strictly necessary; it is policy-dependent whether a separate partition is created).

For our test runs, we used the Mediawiki acceptance tests. The acceptance tests do not cover some crucial functionality, such as image uploads and table processing. We therefore wrote additional test cases using Selenium IDE [4]. Our test deployment includes only core Mediawiki; if Mediawiki extensions are used, test runs should be extended accordingly.

Cimplifier was able to produce a functionality-preserving system of four containers. As expected, the containers need to share some volumes. The ImageMagick and HTTPD partitions share /tmp and /var/www/html. This is necessary because Mediawiki instructs ImageMagick to read image files from /var/www/html and write converted files to /tmp. The HTTPD and MySQL partitions share /var/lib/mysql as MySQL creates a Unix domain socket there, which Mediawiki code connects to. The initial configuration partition shares a few volumes (recall that we enable file sharing by volumes) with other partitions because it needs to write some files to these partitions before starting other services.

While we are able to eliminate most of the redundant resources, our tool failed to reduce 125 MB of Mediawiki code. The reason was that the initial configuration recursively calls chmod and chown on the Mediawiki directory, touching each file there, including test cases and documentation, which could be safely removed. Unfortunately, a pure system calls-based approach, such as ours, cannot distinguish between intentional access and inconsequential recursive access. We also learn that slight configuration changes could result in much better isolation. For example, HTTPD and MySQL need to share /var/lib/mysql (this directory contains MySQL database files) because of MySQL server’s socket there. If however, the socket were created at a different location, this sharing could be avoided. Our next case study shows this.

Wordpress. We study eugeneware/docker-wordpress-nginx, a container that allows running Wordpress [43], a blog engine. It contains Nginx web server, MySQL database, PHP-FPM PHP engine, and Supervisord (a process control system for controlling Nginx, MySQL and PHP-FPM), each of which we would like to be placed in different partitions. The Nginx frontend server connects via a Unix socket to PHP-FPM, which runs Wordpress code and communicates with MySQL for storage through another Unix socket.

Our test runs included performing actions such as creating blog posts, adding comments, changing user profiles, and signing in and out. Cimplifier produced the desired partitions that would together be able to serve Wordpress just like the original container did. It is noteworthy that the configuration of this container allows for better isolation than the previous Mediawiki one: the mysql socket is created in /var/run/mysql and so /var/lib/mysql (the directory holding MySQL files and databases) needs to be present in the MySQL container only.

ELK. The Elasticsearch-Logstash-Kibana (ELK) stack [20] is an application stack for collecting, indexing, and visualizing information from logs, such as those from Syslog or HTTP server. Elasticsearch is used for indexing. Logstash provides network interfaces for receiving logs. Kibana is the web frontend for searching and visualizing logs. We use sebp/elk for our ELK stack. Our desired partitions would be one each of Elasticsearch, Logstash, and Kibana, and one of the startup script.

To exercise this container, we fed it logs from the Linux Audit subsystem [34]. We then performed some simple Elasticsearch queries on its REST API interface. Next, we worked with Kibana to create index patterns, ran some queries on the logs covered by those index patterns, and plotted the query results on various graphs (this is the visualization part of Kibana). Cimplifier was able to produce functional partitions as desired. Except for a log file, there is no file sharing among the partitions; this is expected as the three main components communicate via network only.

Discussion. We note several points from our experience above. First, container configuration highly influences the degree of isolation isolation possible among resulting containers. For example, the location of MySQL socket resulted in the sharing of the entire MySQL data directory with the HTTPD container in the Mediawiki example. However, this issue was not present for the Wordpress container, which created the
MySQL socket elsewhere. Second, the different container partitions sometimes have duplicated read-only resources. For example, the linker and libc are required by all containers and are currently duplicated across partitions. Cimplifier could save space by sharing a layer of files common among partitions (Docker container images consist of read-only layers that can be shared between containers [16]). Finally, as much as 35-67% of the analysis time is spent in recovering a file tree from a Docker image and not in actual analysis. This time can be saved if the file tree were readily available, such as when using the Btrfs storage driver [7].

4.2 Runtime Overhead

We did not find any observable difference in the performance of original and Cimplifier-created containers. This is understandable because programs in the Cimplifier-created containers execute the same way as the original containers. The only overhead incurred is due to the glue of remote process execution but is likely amortized and becomes negligible.

In order to measure the overhead from RPE we wrote a microbenchmark consisting of several iterations of fork/exec calls. Cimplifier results in partitioning at these calls and adding the glue in between, so we can compare the overhead of the glue over the original fork/exec setup. Among the artifacts replicated across containers, the number of open file descriptors and the number of bytes in the command arguments and environment are variable. We show the results of our microbenchmark in Figure 4 (obtained on the same compute platform as that used for our case studies) with both the original and partitioned setup and with varying open file descriptors and arguments and environment length. The RPE overhead increases linearly with these variables. This is intuitive because we replicate these variables in the remote process in userspace. Nevertheless, programs do not use extremely long command arguments (for portability reasons), and even if a program opens a large number of files, the files will typically be closed at the time of exec to prevent file descriptor leakage issues. The overhead per fork/exec is thus only about 1-4 ms for all practical purposes and is easily amortized for any program that runs for more than a few milliseconds.
5 Related Work

A few works in the past have used resource identification for various purposes. In the Docker ecosystem itself, some blog posts and projects have developed automatic container slimming as a solution to the big size of Docker images. All these works [23, 4, 32] have relied on fanotify to identify necessary file resources. This technique is simpler than system call-based identification but does not record crucial file system events like creation and moving of files. Indeed, we have observed behavior such as file moves in real-world containers (such as MediaWiki container that we examined), which would thus break fanotify solutions. Our system call-based approach is more complete. Furthermore, we go beyond slimming to provide container partitioning.

CDE [21] is a tool developed before application containers; it uses ptrace to identify file resources needed for running an application and packs them so as to provide a portable runtime for running the application on any Linux host. While our resource identification is similar, we offer a more formal treatment in a new domain; the other challenges that we address are unique to our work.

Our work draws its motivation from previous work on least privilege and privilege separation. Krohn et al. [22] observe that mainstream operating systems do not provide easy support for implementing least privilege in programs despite wide acceptance of the principle. The evolving container ecosystem also faces this problem, which our work helps address. Provos et al. [31] performed privilege separation of the SSH service manually. Cimplifier is automatic and so can scale better. Brumley and Song [6] developed automatic techniques based on static analysis for automatic privilege separation. Bittau et al. [5] provide operating system-level primitives to allow developing applications in a privilege-separated manner. Others have used specialized programming languages and compilers to ensure flow control across program parts [28, 27, 44]. Program partitioning has also been used in non-security contexts to improve performance [8].

Because of the need to analyze real-world containers running on stock Linux, we have the privilege of neither specialized programming languages nor special OS-level primitives, nor is our problem very amenable to static analysis (Section 2.3). Nonetheless, these works were valuable in inspiring our approach to container partitioning and may in the future be used with our container partitioning approach to offer finer partitions than what we currently achieve.

Another string of related works [41, 40] proposes defenses against resource access attacks that may happen due to confusion between the intended resource and the actual resource access. Our work partially mitigates these kinds of attacks as we place the resources together with the programs in sandboxes protected from outside attackers.

Remote process execution may be compared to live migration. Live migration of processes [18, 30] or virtual machines [12] includes saving all the relevant state and replicating it somewhere else. This includes transfer of the process or VM’s memory as well and usually needs kernel or hypervisor support. In contrast, RPE is a light-weight technique to transfer execution right when it begins. It does not require kernel support but rather takes advantage of a shared kernel state to enable low-overhead, transparent remote execution.

6 Limitations

Cimplifier provides an important first step in container partitioning and slimming. In this section, we point out limitations of our approach and discuss directions for future research. Cimplifier inherits the usual drawbacks of dynamic analysis: if test runs do not cover all relevant scenarios, resource identification will be incomplete. There are at least two promising future directions to mitigate this limitation: (a) design an easy-to-use interface through which a user can guide our tool as to which resources will be necessary; and (b) conservatively expand the resource set to be placed in a container based on patterns seen in resources already being used. Considering a simple example for (b), if a container meant for compiling Latex documents uses *.sty under /usr/local/texmf, a regular expression learning algorithm [3] could be used to deduce this pattern to automatically add all *.sty under this tree, even if they are not used in test runs.

A second limitation is that system calls cannot be used for identifying and partitioning some kinds of resources. Environment variables are one example of resources that may be considered worth partitioning but are not managed through system calls. For such resources, static analysis or an information flow-tracing dynamic analysis may be used to augment our approach.
7 Conclusion

Application containers, such as those provided by Docker, are becoming increasingly popular. We however observe that many Docker containers violate the principle of least privilege by including more resources than are necessary and by not providing privilege separation between applications running in the same container. We designed and implemented Cimplifier, which partitions a container into many simple ones, enforcing privilege separation between them, and eliminates the resources that are not necessary for application execution. To achieve these ends, we developed techniques for identifying resource usage, for performing partitioning, and for gluing the partitions together to retain original functionality. Our evaluation shows that Cimplifier creates functionality-preserving partitions, achieves container image size reductions of 58-95% and processes even big containers in less than thirty seconds.

Notes

1 Linux capabilities are units of privileges that can be independently enabled or disabled. It is thus possible for a superuser process to have only a limited set of privileges.

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