Anception: Application Virtualization for Android

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Abstract—The problem of malware has become significant on Android devices. Library operating systems and application virtualization are both possible solutions for confining malware. Unfortunately, such solutions do not exist for Android. Designing mechanisms for application virtualization is a significant challenge for several reasons: (1) graphics performance is important due to popularity of games and (2) applications with the same UID can share state. This paper presents Anception, the first flexible application virtualization framework for Android. It is implemented as a modification to the Android kernel and supports application virtualization that addresses the above requirements. Anception is able to confine many types of malware while supporting unmodified Android applications. Our Anception-based system exhibits up to 3.9% overhead on various 2D/3D benchmarks, and 1.8% overhead on the SunSpider benchmark.

I. INTRODUCTION

Smartphones have become an attractive target for malware. The number of malicious Android apps is growing rapidly and has reached 700,000+ according to a recent estimate [30]. Rootkits are a particularly serious threat since they can completely subvert the system.

One promising approach to limit the effectiveness of malware is to use virtualization to help confine malware. One implementation of virtualization on Android is the Cells [1] system. Cells allows a single Android device to be used as two or more virtual devices, called “virtual phones”. The user can switch between the virtual phones using a preconfigured user interface gesture. It provides a high-performance approach to support virtual phones. It does not address the problem of isolating a malware application and a sensitive banking application on the same phone. Note that in Cells, each virtual phone is a full Android environment, with its own capabilities to download and install applications and, possibly, its own phone number.

Another possible approach to confine malware is the notion of application sandboxing by using a library operating system (OS). Drawbridge [25] is one such system designed for Windows. As far as we are aware, such a library for Android does not currently exist and porting Drawbridge to Android will, most likely, be a significant challenge due to the vast architectural differences between Windows and Android. More importantly, there are three fundamental drawbacks to using a Drawbridge-like solution on Android. First, Drawbridge uses RDP, Windows Remote Desktop Protocol, for virtualized applications to render graphics on the host system. This approach is likely to be impractical on Android devices because many popular applications, especially games, are graphics intensive. It will also impact the display’s responsiveness to user input.

Second, Drawbridge does not support shared state between applications. Each application is a sandboxed process and sharing state (e.g., files) among processes remains an unresolved problem. Android permits such sharing among applications with the same UID. The UID of an application, in Android, distinguishes the origin of the application, e.g., the vendor and the associated package to which the application belongs.

Finally, Drawbridge does not support multiple processes bound to a single OS library. This is a significant limitation. Fork/clone need to be supported on Android.

This paper describes a novel virtualization approach, called Anception, that provides flexible application virtualization on Android, addressing the drawbacks of previous approaches. Anception provides the following features:

- A notion of containers that provide a lightweight virtualized OS to applications.
- Efficient graphics (close to native speed), with native graphics acceleration capabilities, to all applications.
- Support for binding multiple applications to the same container so that they can share filesystem state, file handles, etc. Furthermore, each container can support multiple processes. Fork/clone are supported.

Anception permits sharing among applications under an appropriate policy. A reasonable policy for the use of Anception is to only allow applications with the same UID to share the container. This would be consistent with the Android security model and would prevent a banking application, provided by a bank, from being in the same security container as a gaming application, provided by an unverified developer. At the same time, the policy would permit the bank app to co-operate with other trusted applications (possibly by the same developer) that share a common persistent state on the file system. With the above policy, Anception does not change the current Android experience.

Anception’s design also provides higher resiliency to a sensitive app from a buggy and possibly malicious app when they are assigned to the same container. A scenario is where a bank provides two apps that share a package name or a shared uid field. One of the apps is for online banking and another is a financial analysis package that may access a common local database between the two apps for calculating balances, plotting trends, etc. The online banking application needs access to the user’s online banking password and is very carefully designed to only keep the password in memory for the minimum time and always send it encrypted to a remote system. The financial analysis app on the other hand, is not as carefully designed and provides an exploit path so that
it can be used by an attacker to acquire elevated privileges on the container. For this scenario it would normally be difficult for the banking app to protect its secrets from the financial calculator and yet be in the same container to share system state. Anception’s memory isolation design allows the banking app to better safeguard the secrets in memory from the compromised financial analysis app.

The key contributions of this paper include:

1) An application virtualization mechanism for the Android kernel that provides good performance for graphics-intensive workloads and allows applications in the same virtual machine to share filesystem state. The solution does not require any changes to existing Android applications

2) Memory isolation among processes in the same container, as provided by our application virtualization mechanism. This guarantee is upheld even when the container is compromised.

3) An efficient system call interposition method to transfer system calls to an application’s virtual machine

To provide the above contributions, Anception uses a novel form of virtualization which we call headless virtualization. With this form of virtualization, security containers for applications are implemented as headless virtual machines, i.e., they do not have the user interface inside the virtual machine; instead the user interface continues to reside on the host, providing close-to-native graphics performance. In Anception, a virtualized application launches from the host but relies on its container to service most of the system calls. This reduces the attack surface available to the application to compromise the system.

Anception is an x86-based prototype, consisting of approximately 5500 lines of code. It requires minimal changes to the Android kernel. Most of the code resides in two Linux kernel modules, one for the host system and one for implementing the containers using guest virtual machines. We created a headless Android userspace stack for the guest virtual machines.

We evaluated an Anception-based system with respect to both security and performance. We analyzed previously reported vulnerabilities in Android and found that Anception provides comparable protection to solutions based on full virtualization. With respect to performance, we analyzed Anception using on several popular benchmarks. Anception incurs a 1.2% overhead on the SunSpider benchmark and less than 3.9% overhead on a variety of PassMark 2D and 3D graphics benchmarks. Power consumption overheads of the Passmark benchmark running within an Anception container was 2.4%. Because of the headless design, Anception containers are memory efficient. They can be launched with 44MB of memory assigned to them versus the 55MB for Cells [1].

Rest of the paper is structured as follows. In section II we present the threat model for Anception based systems. Section III presents the high level overview of the Anception model and Section IV presents the design and implementation details. In section V we present a security evaluation of our model and in section VI discuss the performance overheads. Section VII discusses the limitations of our approach. We present the related work in section VIII and conclude in section IX.

II. ANCEPTION THREAT MODEL

Our current implementation assumes that the base set of applications that are preinstalled on an Android device, e.g., Photo Gallery and Contacts Manager, can be trusted. In principle, they could all be encapsulated in Anception containers for additional security, but our current implementation does not do that.

We assume that the host operating system kernel is trusted and cannot be compromised by a virtualized untrusted app. Except for display (and touch) management services, we provide virtualized equivalents of various privileged Android services (e.g. LocationManagerService, vold) that execute in a container. Untrusted apps may attempt to exploit them to acquire elevated privileges. We assume that a malicious app may completely compromise its container.

We assume that apps may attempt to open /dev devices and issue I/O control operations on them in an effort to exploit bugs in the kernel.

Anception assumes that an application is capable of acting in malicious ways. For example, it can simply ask for more permissions than needed and use them to exfiltrate user data. An application can also execute native code on the device including system calls allowed by the operating system security policy (which is usually most system calls). This often takes the form of local privilege escalation attacks that exploit a vulnerability in some privileged component or framework code.

Finally, our threat model also includes combinations of these techniques wherein a benign application may download an exploit and execute it to gain elevated privileges. It then proceeds to install backdoors and steal user data. However, we cannot protect against all types of privilege escalations. Exploits that involve direct exploitation of a kernel interface are outside the scope of our threat model.

Covert channels are also outside the scope of this paper.

Hardware devices are ultimately shared among all containers. Low-level exploits on the device drivers in the host are outside the threat model. Blocking access to devices, e.g., sensors, selectively for containers is possible future work, based on prior work in the area [4], [22], [33].

III. OVERVIEW OF APPROACH

The Anception model strengthens isolation between groups of smartphone applications and between applications and the host OS by providing a notion of containers (see Figure 1). Containers in Anception are implemented by using lq[uest] [26], a lightweight type II hypervisor. Containers provide resilience against malware that execute privilege escalation attacks. Those attacks, in most cases, are restricted to their container. Containers also provide resource isolation. Apps in different containers do not share filesystem state.

Figure 1 shows the relationship between apps and containers. A container may be associated with one or more apps. A
reasonable system policy is to associate apps sharing a UID with the same container. In Android, apps with the same UID have the same rights and can share filesystem state. We assume this policy. Figure 1 shows three user apps. App X is bound to container A and apps Y and Z are both bound to container B. App X can exchange data within the device with app Y and Z via IPC. Apps Y and Z can share system state such as files with each other and thus have additional sharing channels since they are in the same container.

A downloaded app is bound to a container. The container maintains persistent state of that app. This primarily includes the filesystem state. It also includes the kernel state associated with the app, e.g., state of open files, open network or IPC sockets.

A pre-installed app that comes with the phone need not be bound to a container. As indicated in Section II we trust pre-installed apps not to be malicious. If additional resilience is desired, pre-installed apps could be put in a container.

IPC messages between apps, even across container boundaries, are allowed to maintain compatibility with the Android sharing model. In Android, apps can send requests to each other via intents, which are implemented using ioctl calls on /dev/binder. The system then delivers IPC messages to the recipient(s), subject to access control rules. Recipients can choose to accept or reject the requests. This allows apps to cooperate with each other. For example, Snapchat app can request the Photo Gallery to take a photo. Then, it can request the Facebook app to upload the photo to a user’s Facebook page. Allowing these IPCs is crucial to the Android model.

Providing fast graphics for virtualized apps is generally considered difficult. To allow virtualized apps to get close to native graphics performance, we chose to virtualize an app partially. The app launches normally in the host. Its memory pages reside on the host. User-space instructions execute on the host. Most system calls, including most ioctl, are directed to the app’s container. They are executed by an app’s proxy process in the container. This provides fast display updates and interactive performance at a potential expense of slower filesystem calls. An alternative design would have been to do the graphics operations in the container and use a remote windowing protocol such as X windows, VNC, or RDP. In that case, filesystem operations would be fast but graphics operations would be slower. We provide experimental data in the section on Evaluation that supports our thesis that optimizing user-interface performance is more important than filesystem performance for most apps.

The above design constraint for speeding up graphics implies that all apps must launch from the host. An alternative design is to launch the app from the container but that would have slowed down the performance of ioctl, which are used for sending intents and display-related requests. Those ioctl would have to go back to the host for sending to apps in other containers or for updating the display. That would imply a big context switch from the container’s VM to the host. We avoid most of these context switches by launching the apps from the host. As Section V substantiates, ioctl are very frequent on Android as compared to other system calls.

Given that apps launch from the host, the virtual memory pages of apps reside on the host. But most system calls, e.g., file writes, are carried out on its container’s kernel. This implies that a container’s kernel cannot directly inspect the memory pages of an app that uses it. Conceptually, the container is like a server to the app and manages its system state. This provides an additional layer of protection to apps. We described a scenario in the Introduction where a banking app and a financial analysis app need to be in the same container. As long as the banking app does not write the user’s password to the disk or send it unencrypted over the network, the financial analysis app cannot get to it, even if it is a rootkit. The financial analysis app may be able to totally subvert the shared container, but the container does not have the ability to inspect the banking app’s virtual memory. The container could attempt to core dump the app, but that would cause the host operating system to be the one to dump code. That will be written to the host OS. The container could also attempt to return bad data in system calls to try to do Iago attacks [17]. We are not able to prevent those; the banking app must be designed to be resilient to those attacks. Any critical certificates or keys used by the app must also be part of its code (which are stored on the host side) so that they cannot be tampered with by the container.
from the malicious financial analysis app when they are in the same container. If the code or system libraries were read from the container’s filesystem, the malicious app could modify them and corrupt the banking app.

The device filesystem provides access to various hardware or virtual devices. Some examples are the framebuffer, the accelerometer and Binder. On an Android system, all hardware devices are managed by the system. Thus no app should be able to directly communicate with the device files for these devices. So we just forward these requests to virtual devices in the container. The two exceptions to this policy are /dev/binder and /dev/ashmem. Access to these devices is needed by apps to support IPCs and shared memory. Access to these is directed to the host.

In Anception, each container has instances of standard Android system services. For example, one of the standard system services provides access to the contacts database. An app in a container should use the container’s contacts database. These services are invoked via IPCs. This implies that such IPCs directed at system services, must be redirected to the container.

One exception to the redirection of IPCs to system services is the Notification Manager service that notifies users of notifications from apps. Since user-interface is provided by the host, any IPCs to the Notification Manager must be delivered to the host, rather than to the container.

In Anception, all apps are always installed on the trusted host and launched from there, even though apps are bound to their respective containers. That implies IPCs between two apps that are bound to the same container must be delivered via the host, i.e., such IPCs must not be redirected to the container.

IV. ANCEPTION IMPLEMENTATION

Our prototype consists of two Linux kernel modules (one host, one guest), a few userspace helpers, and a headless Android userspace stack. We use the 2.6.39 x86 Asus EEEPC kernel, Android 2.3 Gingerbread for x86 and an Asus EEEPC ET1602 tablet for the prototype. The implementation is a little over 5500 lines of code. Our changes are minimal and only add a few lines of code to the system call handler, the process descriptor and the fork system call (approximately 30 lines in total). The rest of the code is within kernel modules. The lguest hypervisor is approximately 6000 lines of code. Below, we describe the design of the system.

Figure 2 shows the high-level architecture for implementing Anception containers and Figure 3 shows further details. Each Anception container corresponds to a minimalistic guest virtual machine to provide isolation properties. Apps launch in the trusted system but system calls that could potentially break the isolation properties on Android are intercepted and redirected to the guest virtual machine. On our Android-based implementation, this includes all file-system related calls and most ioctl calls depending upon the level of sharing we wish to configure.

As stated in the previous section, all the user-interface aspects of the app remain in the trusted host system for all the containers. Unlike desktop-based systems, Android already provides strong isolation at the user interface level between apps and we rely on that. Besides speeding up graphics, another advantage of this is that it allows each guest virtual machine to have a small memory footprint.

![High-level Anception Architecture](image)

Fig. 2. High-level Anception Architecture: An app has a proxy in the container bound to the app. System calls that need to be confined are redirected to the proxy.

![Anception Architecture](image)

Fig. 3. Anception Architecture: The Anception kernel module contains the VM independent (left) and VM dependent portions (right).

The host kernel runs a normal Android stack. Applications are bound to guest kernels representing the various containers. The Anception container runs a software stack identical to the host stack in most respects, except in its ability to render to the display or process incoming touch input. That is, the guest is an identical, headless version of the host software stack. The identical portions include the kernel image and framework
code that forms an Android runtime.

When an application is launched, a proxy process is launched inside its container VM as well (see Figure 3). The proxy process sees equivalent privileges, UIDs and directory structures within the guest. The purpose of the proxy is to execute forwarded system calls and return the results. When the process dies, a request is sent to kill its proxy as well.

The architecture of Anception poses a design challenge when it comes to managing memory. An app first launches in the host. At the same time, a proxy process is created in the container to which the app belongs. The app’s page tables and user-space memory resides on the host. But, when it makes a system call, somehow the parameters of that call must be made available to the proxy since the proxy is supposed to execute the call. As a concrete example, consider a system call to open a file. The file has parameters such as the name of the file to be opened. If the system call were executing locally, the kernel can get the parameters by reaching into app’s user-space memory. In Anception’s case, the call is forwarded for execution on a remote kernel. That guest kernel does not have the ability to get to app’s user-space memory.

To address the above problem, Anception marshals all the parameters of the call (in a similar fashion to the seccomp sandbox [29]) and sends them to the proxy. For the above call, the filename would be marshalled and sent to the proxy. The proxy opens the file on its own kernel and gets a file handle. The file handle is returned back to the host system.

Note that system resources, such as actual files and their file handles, exist within the container. The app on the host side gets a handle to a remote resource. That handle can be used in subsequent read/write calls.

Marshalling occurs on write calls as well. Data that is written to a file must be marshalled and sent to the proxy. Fortunately, marshalling turned out to be straightforward for most calls. Also marshalled data for most calls, except for a few such as large file writes, consist of only small amount of data. In a naive implementation, additional data copies would be required – from host kernel to the proxy, from the proxy to the container’s kernel, return of the result from the container’s kernel to the proxy process, and then marshalling of the result from the proxy process to the host kernel.

Fork/clone calls need to be handled carefully. It is not sufficient to fork/clone an app’s process since its file handles really reside with its proxy. Fortunately, the problem is easily solved by also forking/cloning the proxy. So, in reality, each process within an app is bound to its corresponding proxy. Note that the container ID is always inherited whenever these operations take place. A process cannot escape its container through forking/cloning.

The `execve` call is handled in the following way. First of all, nothing special needs to be done to the proxy on an `exec` system call. The proxy continues to store the resource handles. The host process executes the new code. If the binary being executed is a system binary, it is simply executed on the host since the host’s version is identical to the guest’s. If it is a user generated binary, it is copied out from the guest to a special execution cache that is not accessible to the untrusted app, and executed from there. The reason for this is that we don’t want the app to trick the system into copying an executable to a restricted location. Expressing the policy this way is much cleaner. Note that any newly executed binary will belong to the same container as that of the parent.

Dangerous calls like `insmod`, `rmmod`, `shutdown` and others relating to whole system management are denied to applications because no user downloaded app should ever invoke these. Android security model denies them as well.

Android allows a process to create shared memory segments that can be mapped into memory of multiple processes. Handling shared memory segments poses interesting design options. The question is whether these should be created within the host process or in the proxy. The problem is that shared memory segments are often mapped into virtual memory after creation and accessed from code (via the `mmap` system all). Creating these shared memory segments in the proxy would have required intercepting read/write memory operations to the pages corresponding to shared memory segments and transferring them to the proxy, which would not be very efficient.

To address the above problem, mechanisms such as distributed shared memory [20], [17] could have been used, but we chose to go with a simpler solution. We allow shared memory segments to be created on the host. This may appear to introduce a security risk if memory segments could be shared between processes belonging to different containers. Fortunately, that sharing can be easily prevented. In Android, unlike Linux, memory segments cannot be shared by simply knowing the segment name. Instead, Binder IPC calls must be used to communicate memory segment handles. Anception restricts such IPC calls to processes within the same container. Thus, apps in different containers cannot share memory segments.

### A. Management of Apps and Containers

All Android apps are started by a fork from the Zygote process (which is like `init` in Linux). After the fork, Zygote specializes the child into an application by setting its UID and other parameters. We added code to notify the Anception kernel module of this, and we replicate the same on the guest by spawning a proxy, and specializing it. A userspace daemon executes on the host and is responsible for the VM management functions like startup and shutdown. It communicates with the host module through a miscellaneous device node. It is also responsible for binding an application to a container by setting its `vmid` flag to a valid index in the redirection vector. The `vmid` flag identifies the Container ID associated with the app. A value of 0 for `vmid` identifies the trusted host. Higher values identify the application’s container.

This `vmid` value is added as a one byte field in the process descriptor in the host kernel so that a process’s container can be identified by the system. This does limit Anception to at most 256 containers, but that is likely to be more than sufficient in practice.
When an app runs, the Anception kernel module obtains the *task_struct* of the process, and sets the virtualization byte (*vmid*) to the appropriate index value. The *vmid* is inherited by a process’s children. Forking/cloning does not allow a process to escape its container. Also, since this process descriptor is maintained on the host side, compromise of a root service in the container does not allow the app to change its *vmid* and escape the container.

**B. Container Implementation**

Containers run a special version of Android that contains the stock Android system in a guest virtual machine. It has all the core userspace system services found in a regular Android system. The window manager and input manager are nullified by making them talk to dummy devices. Thus, the capability to render and process touch input is nullified. We refer to this as *headless* Android. The point of running this in the guest VM is to provide an alternate, mostly-identical system view to an untrusted process.

Note that apps are not installed inside container images. Thus, all container images are essentially identical, except for state of the apps that are bound to the containers. Furthermore, most of the runtime state of apps resides outside the container, since the memory pages of apps mostly reside in the host (except for much smaller state of the corresponding proxy that runs in the container).

**C. Proxies in an Anception Container**

An app’s system call must be forwarded to its proxy (which runs in a guest container). When a proxy is first started, it is granted the same UID (among other parameters like umask). When a redirected system call arrives at the proxy, we need an efficient way of delegating its execution to the proxy. This means we have to transfer execution from kernel context to the proxy’s process context. One could have a message passing mechanism that notifies a userspace process upon receipt of a system call from the host, but this would require four costly context switches to complete.

Anception uses a more efficient technique that eliminates two of the context switches. We force the proxy process to enter an *interruptible sleeping wait* in kernel space through an *ioctl* on its container’s kernel module. When a redirected system call comes in, we post this call to the container’s kernel, which in turn wakes up the target proxy. After execution of the system call is complete (without leaving the container kernel), the proxy goes back to sleep, in kernel space. This mechanism saves us two context switches over the other option of having the proxy wait in userspace for a notification from the container’s kernel that a system call is to be executed.

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**D. Efficient System Call Interception**

To be able to redirect system calls, one must first intercept a system call. We tried out several system call interception mechanisms – in particular *ptrace*, *kprobes*, *ftrace*, *dtrace*, and *utrace* – but found them to be too slow or limiting. For example, Anception’s first prototype was built using *ptrace* and User-Mode Linux [9]. In this experiment, we bound untrusted processes by ptrace-ing them. However, microbenchmark tests indicated overheads upwards of 60x (primarily due to a high number of context switches). In Android, all applications derive from Zygote. During a ptrace session, reparenting occurs, and this may cause unintended side-effects. Other mechanisms, primarily debugging or tracing mechanisms, were also not efficient enough for our purposes.

We decided to design our own system call interception mechanism that was suited for transferring the call to a proxy process in a different container efficiently. The system call interception mechanism incurs an overhead of just a few instructions on the host system. The basic insight was that we could create a different system call table per container and then provide an efficient way of redirecting a system call to the appropriate table, based on the app’s container ID (which is available in the *vmid* value in the process descriptor as described in part B).

Figure 4 shows the details of a system call. When an application process makes a system call (step 1), control is transferred to the system call interrupt handler (step 2). At that stage, we analyze a field in the process descriptor, named *vmid*, that allows us to identify the container that is bound to the process. A value of 0 indicates that the process runs directly on the trusted host and no redirection should occur. If *vmid* is greater than 0, its value specifies an index into a redirection array. The redirection array is a set of base addresses for various system call tables corresponding to the various containers. The implementations of system calls will serialize call arguments (step 3) and transfer them to the guest kernel via the *virtio* transport (step 4). Once the call has been executed by the host process’s proxy, the results are returned either via *virtio* or via a hypercall (step 5). Finally, the results are returned to the original process that initiated the call.

**Fig. 4. Anception Architectural Detail**

System call interposition has been the topic of much research in the past, several problems have been identified [10], and solutions have been developed [11], [31]. Our system call
interposition method follows several best practices outlined in previous research [11], [31], [19], while avoiding the problems encountered while building systems such as in [12], [15]. Some representative problems include time-of-check-time-of-use (TOCTOU) attacks, and symlink races. The choice of which syscalls to intercept has been influenced in part by the REMUS system [5].

Our streamlined implementation of system call interception adds a few assembly lines to the system call interrupt handler. In practice, this is efficient. Furthermore, the amount of architectural state we save to intercept and redirect is negligible. For details, see Table I. The minimal runtime overhead of the system call interception is reported in Section VI-A.

In Anception if the apps were appropriately assigned to the Anception containers and appropriate policies for network communication governed those containers.

Seven involved system services that could be manipulated by malicious apps to escalate to root privileges or obtain sensitive system information (see Section V-B).

Another seven were serious Linux device driver vulnerabilities. These included four instances of poor bounds checking on memory operations within graphics and diagnostics drivers. A further two vulnerabilities were instances of improper dereference and use of pointers to user space that were passed as arguments to ioctl. In these six cases, the vulnerable driver code is accessed by first opening the device file corresponding to the vulnerable driver and then performing an ioctl system call to send a request to the driver, which would contain the exploit payload. In our experience, there would never be any reason for an ordinary app running on Android to access any device files directly other than binder and ashmem, both of which are vital services intended to be used by all applications, e.g., for sending intents and shared memory. Anception redirects any open system calls for drivers other than these two to the guest container, in turn confining the vulnerability to the guest container.

On Cells, there is a higher risk that the above device driver vulnerabilities will not be confined. There is only one kernel in Cells shared by all the containers. If the device driver in question is virtualized as well or disabled in a cell, then there may be a possibility that the exploit could fail.

Finally, there was one instance of a driver file that provided read and write access to physical memory and was configured as world readable and writable by the vendor. Again, Anception would prevent it since read/writes to such files would be redirected to the container.

Finally, one vulnerability in the Linux kernel allowed an attacker to compromise physical memory by triggering a null dereference in code related to network socket operations. Since Anception redirects these system calls, they would only compromise the container that a malicious app was bound to.

Anception does present a different attack surface than full virtualization and Cells. Since the display-related activity takes place directly on the host, bugs in that could potentially be used to exploit Android. We were unable to find such exploits.

B. Example Exploit Walkthrough – Gingerbreak

Anception prevents most rootkit attacks. To understand how, we present a concrete example of the Gingerbreak exploit.
Gingerbreak is a local privilege escalation based on a negative integer array access in vold, the volume manager on Android. It has been used by a number of malware applications [16] as a method to gain superuser privileges and nullify the Android security model. Below, we summarize the steps that occur when that app is running in an Anception container.

1) Gingerbreak starts out by making a copy of itself by reading /proc/self/exe and writing to the malicious app’s private directory. With Anception, the write will be redirected to the app’s private directory, which is an identically named and configured directory in the app’s container. Thus, a copy of the exploit’s executable will be made in the app’s container.

2) The exploit then proceeds to its information gathering stage. The first step here is to find the vold daemon by its process identifier. It does this by opening /proc/net/netlink. With Anception, this open system call will be redirected to the app’s container and the exploit will read the container’s runtime information of the netlink environment. We have an identical environment in the container.

3) The exploit then searches procfs for /system/bin/vold and makes a note of the corresponding PID. As stated in Section IV with Anception, the system calls to find the pid will be forwarded to the app’s container. Note that now, the Gingerbreak exploit executing on the host has obtained the PID of the vold executing inside the container.

4) The exploit then proceeds to find the address of vold and strcmp inside /system/bin/libc.so. As applications execute on the host, and any useful application will use libc, Anception simply allows opens and reads to execute on the host for such system code libraries.

5) The exploit, in the next stage of information gathering, attempts to find the Global Offset Table (GOT) start address of vold. The Gingerbreak exploit does this by opening the vold executable and using the ELF-32 API to parse it. The exploit then looks for the last piece of information to find the storage device that vold manages. System files are involved in the reading process and as per our rules, we let them go through on the host itself since these files are read-only.

Coming to the actual privilege escalation, Gingerbreak needs to find the negative index value to send to vold so as to achieve code execution. It uses a brute force approach by trying values in a range and then scanning the logcat crash logs for failed attempts. The exploit creates its own logcat log file (which is redirected and created in the app’s container), kills logcat (which is mirrored in the app’s container as well), and then restarts it by specifying its own file as the log file (also restarted in the app’s container). Note that as per Anception’s rules, when a fork/exec occurs, we simply let the fork happen on the host, but the new process is bound to the app’s container; the sandbox is extended to the forked process. Since the new logcat is bound to app’s container, it sends its output to a file that only exists in that container.

Once an index has been calculated, Gingerbreak forms a netlink message and uses socket calls to talk with the vold process. With Anception, Gingerbreak sends shellcode with the negative index to vold inside the container. This causes vold to execute the exploit binary that was copied into the container. The exploit always checks on execution whether its uid is 0. Since vold started it the second time in the container, the root check succeeds and the exploit has succeeded inside the container VM. As the container is isolated via system virtualization, the host remains protected.

VI. Performance Evaluation

Anception’s design decision is to launch the applications from the host rather than within the container and not direct graphics operations. To verify that it is the right design choice for Android, we conducted a small experiment to measure the relative frequency of UI updates and touch events as compared to other class of operations. We ran five regular applications available on almost every phone - Email, Web Browser, Music, MMS, Default Game. As we see in Table III over 92% of the system calls made are UI-related. A similar study measuring categories of system calls was conducted by ProfileDroid [32] as well. The results from both studies serve to confirm our hypothesis.

| Service Requested       | Total Count | Percent  |
|-------------------------|-------------|----------|
| android.accounts        | 2           | 0.00%    |
| android.app            | 1769        | 2.96%    |
| android.content         | 1611        | 2.69%    |
| android.media          | 16          | 0.03%    |
| android.net            | 4           | 0.01%    |
| android.os             | 122         | 0.20%    |
| android.ui             | 48646       | 81.35%   |
| android.util           | 979         | 1.54%    |
| android.view           | 2004        | 3.35%    |
| com.android.internal.telephony | 82 | 0.14% |
| com.android.internal.view | 4619 | 7.72% |
| ImountService          | 1           | 0.00%    |

**TABLE III**

Counts of various Binder IPC ioctlS issued to Android services. Note that UI dominates other types of requests.

Next, we run a microbenchmark to analyze the overhead of the VM-independent system call interception framework. We run two popular Android macrobenchmarks to analyze whole system performance and one application level benchmark to analyze the impact on end users. The macrobenchmarks are used so that we can measure the performance for interactive workloads that are the most common for smartphones. We also report on the memory consumption of the guest VMs.

All the benchmarks are run on an Asus EEEPC ET1602 equipped with an Intel Atom x86 processor, 1GB of RAM and 160GB of internal flash memory. The EEEPC runs Android x86 version 2.3.7 with Linux kernel version 2.6.39. We
configured the guest VM with 64MB of main memory that ran our headless Android port.

A. Microbenchmarks

We run a microbenchmark to measure the latency of performing 3 common system calls with the Anception Syscall Interception Method (ASIM) activated. We measure the time for a null-redirection, which is intercepting a syscall and redirecting it to the real system call handler. The benchmark executes the syscalls 10,000 times and uses the x86 cycle counter for timing. Trial runs are executed by the benchmark to warm up the caches. The results for the ASIM are summarized in Table IV. The write, read calls are executed on files.

| syscall       | Native (µs) | Anception (µs) |
|---------------|-------------|---------------|
| getpid        | 0.57        | 0.57          |
| write (32 bytes) | 17.7       | 17.8          |
| read (32 bytes)   | 3.3         | 3.4           |

**TABLE IV**

ASIM LATENCY

As we can see in the table, the ASIM adds negligible overhead and is very efficient. The next microbenchmark measures the round-trip time for a system call when redirected to an active guest VM. The results are summarized in Table V.

| syscall       | Native (µs) | Anception (µs) |
|---------------|-------------|---------------|
| write (16 bytes) | 24.9       | 206.9         |
| read (16 bytes)   | 3.4         | 203.2         |
| write (32 bytes) | 17.7       | 196.6         |
| read (32 bytes)   | 3.3         | 212.7         |

**TABLE V**

FULL REDIRECTION ROUND TRIP TIME

The increase in latency is caused due to two VM switches (host → guest, guest → host) and process context switches. As context switch times go down due to improvements in hypervisor technology, we expect to see reductions in the latency. However, these numbers do not adversely affect performance at a macro level, which is what we report on next.

B. Macrobenchmarks

We run three popular Android macrobenchmarks – PassMark [24], AnTuTu [2] and SunSpider [28]. These benchmarks are designed to test 2D and 3D graphics performance, Disk I/O, Memory I/O and CPU (Java, Native) performance. They report a weighted total score, and individual scores. Running 2D/3D benchmarks enables us to analyze the overheads caused by our ioctl handling logic. It should not cause a large overhead because graphics related ioctls form a large chunk of the system calls executed by applications (Table III).

The PassMark benchmark reports details of the tests conducted. Figure 5 shows us that Anception incurs negligible overhead for a range of 2D and 3D graphics tests. They also show no noticeable change. Overhead of 3.88% is incurred on 2D tests and 2.64% on 3D tests. In terms of CPU and Memory I/O, as reported by PassMark, Anception incurs 0.43% overhead on memory operations and 2.3% overhead on CPU operations. This slight increase is due to the guest VM running Headless Android that puts additional scheduling and memory pressure on the host. However, due to our architecture of handling UI operations on the host, the impact of this VM is negligible.

![PassMark Benchmark](image)

On the AnTuTu Benchmark, Anception’s score was 3.6% less than native, with a 0.4% overhead on the 2D tests and 1.3% overhead on the 3D tests. To get an idea of Anception’s performance with interactive and application oriented workloads, we run the SunSpider [28] Benchmark. At a macro level, from Figure 6 we observe that Anception closely follows the performance of native execution with a 1.2% maximum overhead among all tests. This benchmark also shows our ability to run unmodified Android applications on Anception. The reason for the modest overheads is the ioctl identification code wherein we determine whether a particular IPC operation is related to graphics and input operations.

![SunSpider Benchmark](image)
C. Memory overhead

Finally, we quantify the memory (RAM) savings earned by using a headless version of Android. To measure this, we read the `/proc/meminfo` file on a stock Android 2.3.7 system, and we read the meminfo file on a headless instance. These readings were taken when the systems were just booted up and just the bare essentials were running. For a stock Android system, the number of active bytes of memory is 99.11 MB. On the headless version, it is 14.87 MB, or 15% of stock Android. This is much smaller compared to 40% of stock Android that is needed by Cells to start a guest VM. Moreover, we have not applied optimizations like Kernel Samepage Merging (KSM) that Cells has applied to its implementation. We expect to see further reductions with KSM in place. The reason for the decrease is again due to Anception’s architecture. By running a Headless Android instance in the guest VM, the memory used up by Display Managers and Input Managers is freed up, allowing us to run smaller sized (in terms of RAM) VMs. However, during all our experiments, we started the guest VMs with 64MB of main memory, although we could have started them with as low as 44MB of memory. We did not do this as we didn’t want to adjust the Android low memory killer parameters.

D. Power Measurements

Smartphones are resource constrained devices and usually have limited battery power. In order to ensure that the effect on energy consumption due to Anception is not significant, we conducted several experiments on the PassMark and SunSpider benchmarks to quantify the overhead. We used a Watts Up? .Net power meter for our measurements on power and energy consumption. Using the MonkeyRunner feature provided by the Android platform, we built automated tests to run the benchmarks for an hour each, both with and without Anception enabled. In order to simulate the actual execution of an application, the benchmark was exited using the back button after every run. For the PassMark benchmark, we observed that the energy consumption was 20.8 Watt hours without binding it to Anception and the consumption went up to 21.3 Watt hours upon binding, giving an overhead of 2.4%. For the SunSpider benchmark, energy consumption without Anception was 34 Watt hours and on binding the consumption went up to 35.3 Watt hours indicating an increase of 3.82%.

VII. LIMITATIONS

As Anception is a research prototype, we acknowledge a few limitations of the system.

As we described in Section IV intent requests to all Android system services, except for the touch display, are directed to the container. If an app sends a request to the Location Manager to get the GPS readings, the IPC request will go to the guest and then be delivered to the Location Manager in the container. That Location Manager will talk to a virtual GPS device. Then, it is a matter of policy whether the virtual device should be permitted to talk to the real device on the host via a narrow interface. Our research prototype has not implemented these mappings from virtual devices to physical devices, but the technology to do that is well understood. Most virtual machines, such as VMware, have that capability.

The Linux kernel allows certain system calls to be implemented by drivers. Examples include the `ioctl` or VFS system calls (`read`, `write`). Since these are relatively new implementations, they can be buggy. As Anception does not redirect all system calls all the time, it can happen that some system calls that go to such buggy drivers are executed on the host. In such cases, Anception is unable to provide sufficient isolation so as to protect the integrity of the host. However, this is an area of current research and we could build upon other solutions in the literature designed to tolerate buggy drivers.

UI system calls and related non-redirected system calls could themselves contain bugs. As such calls are always executed on the host, there is a small chance that they could be exploited by malicious apps. However, given that such calls are heavily used, it is likely that most errors have been corrected.

Anception only supports memory-mapped file I/O partially. If a file is in the read-only part of the file system (e.g., `/sys` on Android), those can be memory-mapped since the I/O operations on those are directed to the host. Memory-mapping in the writeable portion of the filesystem is not supported. Those files reside in the container. This is not a fundamental architecture limitation. NFS-mounted files can be memory-mapped. A possible strategy for implementing that would be to provide an NFS-style access for the host to a container’s filesystem.

Anception does not currently use kernel same page merging optimizations [18]. The results from the Cells paper show that those optimizations can significantly reduce the memory requirements for multiple containers. We expect containers to have a high degree of overlap in pages since, except for the small proxies to hold system-relevant state, the memory pages of an application reside on the host.

Anception currently only supports the simple policy that only apps having the same UID are assigned the same container. It would be interesting to explore other types of policies. For example, all work-related apps could be assigned to belong to one container and personal apps belong to another container. In that case, Anception can be used as a platform to support multiple virtual phones, as in Cells [1].

VIII. RELATED WORK

We categorize the related research into several classes and draw on ideas and techniques from several of them.

A. OS Virtualization

Systems based on paravirtualization such as VMware [3] and Xen [14] as well as Cells [1] can provide a full virtual container for the entire operating system. Cells, in particular, is a good solution for virtualization on Android if the goal is to support multiple virtual phones. It uses a single shared kernel. The goal of Anception is to provide application-level encapsulation. It may be possible to provide Cells-based
Anception where, instead of using lguest, cells are used to provide containers. This would require a substantial redesign as, currently, each cell provides a full Android environment with its own set of apps. Conversely, it may be possible to provide Cells-like virtual phones using Anception as a platform. It will require significant changes to Anception’s handling of IPCs (cross-container IPCs will need to be forbidden) and apps will need to be allowed to be associated with multiple containers.

The recent ExpressOS system [21] by Mai et al is an OS built in a type-safe language. The aim is to build a small verifiable OS kernel that is able to run apps with high assurance of the services provided to them. ExpressOS provides a secure storage service (among others) that guarantees data written to disk is not tampered with or disclosed to an untrusted Android runtime. The difference with Anception is that ExpressOS does not strengthen the isolation between trusted and untrusted apps. If an application is benign but buggy, ExpressOS does not provide protection against exploitation by other apps. ExpressOS is complementary to Anception in addressing a different threat model.

VirtuOS [23] by Nikolaev and Back is a modified Linux environment that isolates device drivers in virtual machine containers, which run in parallel to improve performance on multicore environments. Anception does not address device driver security. VirtuOS is complementary to Anception in addressing a different threat model.

Anception builds on techniques from several systems. The Pods system [19] uses system call interposition as the mechanism for virtualizing a process’s view of the OS. Linux Containers is another mechanism being integrated into the Linux kernel, which will allow a user to establish isolated containers via a tool called LXC. Linux Containers use a namespace mechanism to isolate and virtualize resources directly from within the kernel. The interposition mechanisms of Pods and Linux Containers has similarities to that used in Anception. Both Pods and Linux Containers are full solutions that handle virtualization of an entire guest system. In this way, they are interchangeable with lguest in our implementation of Anception, but do not include any policy for deciding which system calls are worth keeping on the host for performance reasons. Because of this, we view them as complementary tools to our work.

Overshadow [8] provides mechanisms for applications to protect their state from compromised kernels.

B. App Sandboxing

Providing strong isolation on Android is mostly centered around policy based approaches. TrustDroid [6] monitors IPC channels, network and filesystem accesses through extensive modifications to the Android framework and prevents apps in different trust domains from talking to each other. Unlike Anception, an untrusted app in TrustDroid executes entirely on the host kernel, as there is only one kernel. That potentially makes TrustDroid vulnerable to native code exploits via system calls that would be forwarded to the guest kernel in Anception but are executed on the host kernel in TrustDroid.

AppFence [13] prevents access to a user’s private data (e.g., contacts data) by providing false or pre-recorded data to untrusted apps, based on policy. AuraSium [33] inserts inline reference monitors in untrusted applications and monitors their interactions through the system calls made. In some cases, it rewrites system call arguments and return values (at the libc level) to enforce certain types of policies.

Janus [12] is a user-level tool that allows users to sandbox applications and implement a policy that determines which system calls they are allowed to execute. If a particular system call invocation is not expressly permitted by the user-specified policy, it is discarded and returns an error to the calling process. Anception is much more flexible than this, in that it provides an isolated environment in which risky calls can execute safely, rather than simply denying them.

Wine Windows Emulator on Linux and Drawbridge for Windows [25] provide a linkable user-space OS library that encapsulates an entire Windows OS to which executables can link to. Part of the goal of these is to allow applications to be portable across different versions of Windows (they can be distributed bundled with the OS library). But, another potential use of Drawbridge, in particular, is to sandbox individual applications. There are some similarities in that Anception also allows individual applications to be sandboxed but there are also some differences in both design and philosophy. Drawbridge uses Windows Remote Desktop to allow encapsulated apps to share a common display. Anception’s apps have direct access to the Android display, which, by design, should have lower latency and be more efficient on mobile devices, especially for gaming apps that are highly interactive. Anception allows multiple applications to be assigned to a common sandbox, i.e., Anception containers. Drawbridge applications cannot share system state.

C. File System Isolation

Android recently incorporated a multiuser feature that helps in setting up multiple user accounts and sharing of a single device. Each user is assigned a unique user ID and corresponding directory on the filesystem (/data/users/ID). When the device switches to a user, symbolic links are set up from an app’s directory (/data/data/APP.PKG) to the private user directory. This enables backwards compatibility and makes a profile switch efficient, but the overall design has drawbacks. If an owner wants to share an app, he must first create a secondary profile, switch profiles and reinstall the app into the new profile. If the owner uses his own Google account, various settings can be imported into the other profile, causing privacy leaks. Direct sharing from the primary user profile is not possible, although there are community built apps that enable such sharing. These have the disadvantage of sharing all private data from the owner’s profile with the secondary profile.

D. Information Flow Techniques

Moses [27] is a system that provides isolation among apps in different trust domains. The main disadvantage of Moses
is that it requires heavyweight taint tracking at run-time to detect and prevent undesirable information flows. Moses uses filesystem virtualization (namespaces) to provide a different data directory to an app. This allows an app to maintain different profiles by switching filesystem namespaces. This supports sharing of apps easily but does not provide a secure and isolated execution environment for untrusted apps.

IX. CONCLUSION

Current virtualization solutions, although useful, fall short of user expectations. Anception proposes a headless virtualization model that achieves a balance between isolation strength, user experience, and system performance while protecting a user’s internal (on-device) and external (online) data. Through a combination of system call redirection and system virtualization, Anception provides the technology to run a subset of an app in an isolated, virtual container while maintaining correctness of execution. An exhaustive evaluation of Anception in terms of security guarantees and system performance revealed overheads of up to 3.88% on various 2D and 3D benchmarks and up to 3.82% additional power usage, as well as comparable isolation guarantees to existing virtualization mechanisms, showing that Anception is indeed a practical system. As future work, we aim to investigate other forms of system virtualization like namespaces, while keeping kernel changes modest and maintaining security guarantees.

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