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**Thesis Title:** Real-time capturing of system calls on ARM

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# REAL-TIME CAPTURING OF SYSTEM CALLS ON ARM

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**[ABSTRACT]:** Reproducing bugs is difficult. In areas such as application development, developers often encounter errors reported by users. They often have to rely on the report logs uploaded by the user to try to reproduce these failures. Unfortunately, bugs are usually not reproduced such faithfully. This is mainly because the execution of a program is always accompanied by many non-deterministic events. The recording of these non-deterministic events is an effective way to address this issue. Meanwhile, it is noticeable that system calls are the primary source of non-deterministic events, hence we need to capture these system calls.

In this thesis, I developed a system call capturing tool. This tool utilizes Linux Tracepoint to record system calls across the entire system, or filtering by user-determined constraints, with low overhead and transparent trapping.

To demonstrate the effectiveness and the efficiency of my research. I evaluate it with real-world bugs and compare it with the state-of-the-art systems.

**[Keywords]:** Linux, Syscall, Record

# Contents

<b>1. Introduction</b>	<b>2</b>
<b>2. Background: Linux Trace</b>	<b>3</b>
<b>3. Design</b>	<b>3</b>
3.1 Challenges	4
3.1.1 Syscall parameters	4
3.1.2 Record Buffer	4
3.2 Design Overview	5
3.3 Core Hook	5
3.4 Filter	6
3.5 Record Buffer	6
<b>4. Implementation</b>	<b>7</b>
4.1 Core Hook	7
4.2 Filter	7
4.3 Record buffer	7
<b>5. Related Work</b>	<b>7</b>
<b>Bibliography</b>	<b>8</b>

# 1. Introduction

The program would often fail. To sufficiently understand and prevent failures, developers requires firstly reproduce these bugs, which ensures the same output and bugs no matter how many times it is re-executed. However, directly re-execution is not suitable for non-deterministic failures, as they may not appear in a re-execution procedure. Non-deterministic failures are the consequence of non-deterministic instructions.

Instructions for running a program can be divided into two categories. One is deterministic, i.e., the behavior of the program is determined in each execution. The other type is non-deterministic, meaning that execution in different situations will have different results. Although most of the CPU execution is deterministic, non-deterministic instructions are also pervasive. This is mainly because of the fact that the execution of a program is not in an isolated system. In fact, the operating system plays a critical role in program initialization, system calls, and scheduling throughout the program lifecycle. Typical sources of nondeterminism include system calls, interrupts, signals, and data races for concurrency programs.

All these non-deterministic events can be further classified into two types: inconstancy of the data flow - for example, certain system calls such as `getrandom` and `getpid`, and inconstancy of the control flow - for example, concurrency bug due to memory access in inconsistent order<sup>[1]</sup>.

Record-and-replay is a type of approaches that addresses this challenge. Most Record-and-replay systems work by first recording non-deterministic events during the original run of a program and then substituting these records during subsequent re-execution. Record-and-replay system could ultimately guarantee that each replay will be identical with the initial version. The fact that a number of replay systems have been built and put into use in recent years illustrates the value of record-and-replay systems in practice<sup>[2-5]</sup>.

There is a rich amount of research on record-and-replay systems, and we can find their various treatments of non-deterministic records. Early record-and-replay systems tend to use virtualization techniques so as to observe and record the entire program non-deterministically on the hypervisor, but the virtual machine is very heavy<sup>[6, 7]</sup>. Some systems use dynamic binary instrumentation to get the results after running each instruction, but this is very inefficient<sup>[5]</sup>. There are some other systems that choose not to record at runtime in order to address the expensive cost of recording; instead, they infer these non-deterministic events based on the control flow and other information collected.<sup>[4, 8]</sup> However, inference often does not reproduce program execution as faithfully as records, and the time required for inference, which in the worst case is a search of the entire space, is a problem<sup>[3]</sup>. There are also systems that use custom hardware, which inevitably affects its usefulness in practice<sup>[9]</sup>. Recently there have been some practical systems that have adopted tools provided by Linux for trac-

ing, thus achieving better efficiency. Nevertheless, it still introduces a considerable overhead (50%) and is therefore used in scenarios where the developer exactly needs to debug<sup>[2]</sup>.

This thesis focuses on the data record part of record-and-replay systems, precisely, the logging of non-deterministic events caused by system calls. I argue that a *practical* record system should (1) run online, meaning that the recording has little performance impact on the execution of the target program, (2) log all data without any omission, (3) work on commercial off-the-shelf hardware, (4) not require any modification to the target program, and also (5) not require any modification to the kernel.

In this thesis, I propose `PROJECT_NAME`, a practical solution for syscall capturing. It works effectively on Linux, on commercial off-the-shelf hardware, and it can run almost imperceptibly along with the original program.

## 2. Background: Linux Trace

From trace maker to tracepoint

## 3. Design

The overarching target of `PROJECT_NAME` is to capture all syscalls issued by target application with low overhead. Specifically, it has the following characteristics:

- **online:** Our scenario is that our entire record system can work simultaneously on the user side and eventually become a part of the log report. Therefore it must introduce only a extremely low overhead to guarantee that the user can run the desired program without perception.
- **complete:** We also need to ensure the integrity of record results, i.e. that every syscall is correctly captured with all the data needed for reproduction. Not only do we need to verify the correctness of our records on each syscall, but we also have to guarantee that the data in the buffer is fetched in a timely manner without any overflow.
- **off-the-shore:** An practical system should never make assumptions about the hardware. `PROJECT_NAME` is desgined completely based on the off-the-shelf hardware.
- **without modification to application:** We do not make any changes to the source code or binary of the target application. The entire code of our system runs in kernel space, except for the transfer of logged results that need to be transferred to user space. This means that `PROJECT_NAME` cares nothing

about how the target application in user space is executed, but only about the event that this target application jumps to the kernel state.

- **without modification to kernel:** Modifying Kernel source may make all procedures much more easy. However, this approach will inevitably reduce the compatibility of `{PROJECT_NAME}`, especially for devices whose kernels have been modified by manufacturers. Furthermore, to modify kernel, we would also need to synchronize upstream changes. Consequently, `{PROJECT_NAME}` is based on kernel module and works as a loadable driver.

`{PROJECT_NAME}` realizes syscall capturing in three steps. (1) `{PROJECT_NAME}` inspect and record each syscall. (2) Next, `{PROJECT_NAME}` filter these records by some attributions of its caller process. (3) Finally, `{PROJECT_NAME}` transfer these filtered records.

### 3.1 Challenges

To achieve its design goal, `{PROJECT_NAME}` faces following challenges.

#### 3.1.1 Syscall parameters

Considering some syscalls that allow to pass pointer and then modify its memory addressed by this pointer, it is necessary to check and record the change. For example, the prototype of syscall `getrandom` is defined as follow:<sup>[1]</sup>

```
ssize_t getrandom(void *buf, size_t buflen, unsigned int flags);
```

It is clear that the `getrandom` will fill the buffer pointed to by its first parameter, `buf`. Therefore, `{PROJECT_NAME}` needs to record the memory area changed by syscall. However, there is still a challenge that sometimes we cannot get the address at the end of syscall invoked. This is due to the way the parameters are passed, determined by the architecture of CPU.

In Arm64<sup>[10]</sup>, both first argument(`arg1`) and return value are saved in register `r0`, which means the parameter stored in `r0` will be replaced with return value before the syscall return to user. This results in the inability to directly record the changes only at the end of syscall handled in kernel. I solve this challenge by adding an extra record for several syscalls.

#### 3.1.2 Record Buffer

System call records need to be stored in a buffer, while it is a very important issue when it comes to somehow get them from the buffer in real-time, with low consumption, and completely. However, the most straightforward solution, i.e., trying to keep fetching data from the buffer and save to file, causes a huge amount of overhead. I solve this challenge by enlarging buffer and reducing the frequency of acquisition.

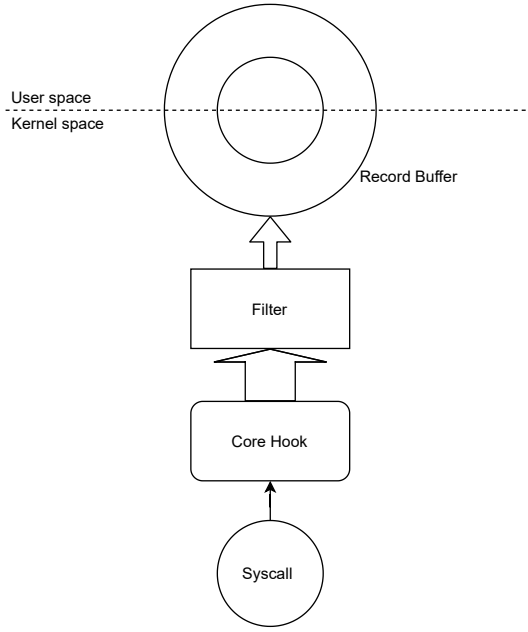


Figure 1: The three parts of  $\{\text{PROJECT\_NAME}\}$

### 3.2 Design Overview

In this section, I present the design of  $\{\text{PROJECT\_NAME}\}$  by focusing on how it addresses the above two key challenges.  $\{\text{PROJECT\_NAME}\}$  contains three parts: *core hook*, *filter*, and *record buffer*.

As Figure 1 shows, in the kernel space, *core hook* defines callback functions in syscall, and will firstly inspect each syscall and then transfer relevant information to *filter* part. Subsequently, at the *filter* part, it will find process information from the kernel, and filter syscall records with specific features (e.g., process id or name) and finally pass to *record buffer*. The record buffer has two components: buffer management in kernel space and fetch daemon in user space. The daemon in user space will check the buffer periodically and dump these data from buffer to file.

### 3.3 Core Hook

Figure 2 shows the general workflow of *core hook*. It consists of two stages of hooks, at the beginning and end of kernel handling of syscall. For the stage 1,  $\{\text{PROJECT\_NAME}\}$  will follow the start of syscall handlers and save the value of first parameter, if this syscall may change the memory addressed by first argument.

The second stage takes on more responsibility, including the recording of other pointer type parameters (except for the first one), and return values. Besides, this stage should also get the relevant information collected by stage 1.

There is still a problem that, due to the concurrency of the system, there may be

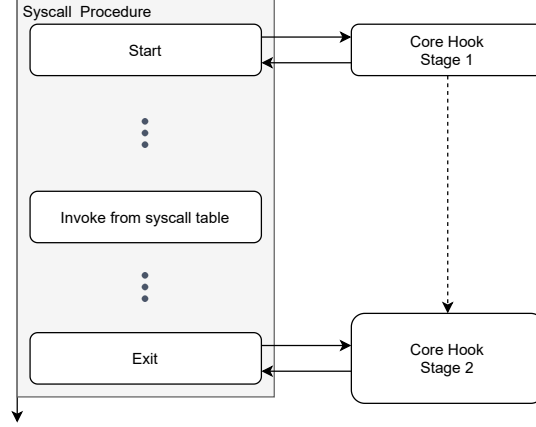


Figure 2: The two tages of *core hook*

multiple system calls being processed at the same time. Especially considering that the system calls processed in a relatively long period. So, there will be multiple system calls going to different stages of *core hook*.

This problem is solved by the observation that syscall will block the thread in user space. Therefore, we can find a one-to-one mapping from thread number to a system call event at any moment. I maintain a table to save these correspondences in second stage, and also get its first parameters from stage 1.

### 3.4 Filter

The **filter** part is a relatively simple component that requires information about the caller of the syscall from the Linux kernel. Then it will perform filter by pre-passed conditions. Last, it passes this filtered information on to the next part.

### 3.5 Record Buffer

The *record buffer* is intended to act as a transit between kernel space and user space. Therefore it has two parts located in kernel space and user space respectively. One of the simplest designs is to maintain a daemon in user space constantly querying and retrieving the data stored in the buffer, and then dumping the data to a file. However, we note that this introduces a huge amount of overhead, mainly due to frequent file io. Placing a larger buffer in user space would also solve this problem, but `{PROJECT_NAME}` do not want to introduce a large impact on the entire system.

Therefore, *record buffer* is designed to keep fetching the buffer occupancy, and then dumps the whole buffer only after finding that the buffer occupancy has reached a threshold.



## 4. Implementation

### 4.1 Core Hook

The part of *core hook* aims to hook system call, i.e., inject custom code at the begin and the end of a system call. By leveraging *core hook*, It is easy to get the return value of the system call and the changes to the parameters. Linux has provided many different approaches to achieve it, such as *ptrace*, *auditd*, *Kprobe* and *tracepoint*.

I choose *tracepoint* to implement our core hook, since it

### 4.2 Filter

We get the process descriptor of syscall issuer (the process using the syscall) via `current`, and compare it with conditions passed in.

### 4.3 Record buffer

The buffer is a circular queue. And there is also a number indicating the usage of the buffer.

The most sophisticated component is to share the buffer between kernel space to user space.

## 5. Related Work

There is a large amount of related work dedicated to capturing syscalls. In this section, I discuss some representative examples and describe how `PROJECT_NAME` differs.

- **Pinplay** is a ...
- **REPT** ...
- **rr** ...
- **DTrace** ...
- **sysdig** ...

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