Measuring Attack Surface Reduction in the Presence of Code (Re-)Randomization

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Abstract—Just-in-time return-oriented programming (JIT-ROP) technique allows one to dynamically discover instruction pages and launch code reuse attacks, effectively bypassing most fine-grained address space layout randomization (ASLR) protection. However, in-depth questions regarding the impact of code (re-)randomization on code reuse attacks have not been studied. For example, how do starting pointers in JIT-ROP impact gadget availability?; how would one compute the re-randomization interval effectively to defeat JIT-ROP attacks? what impact do fine-grained randomization and re-randomization have on the Turing completeness of JIT-ROP payloads? We conduct a comprehensive measurement study on the effectiveness of fine-grained code randomization and re-randomization, with 5 tools, 13 applications, and 19 dynamic libraries. We provide methodologies to measure JIT-ROP gadget availability, quality, and their Turing completeness, as well as to empirically determine the upper bound of re-randomization intervals in re-randomization schemes. Experiments show that instruction reordering is the only fine-grained single-round randomization approach that thwarts current gadget finding techniques under the JIT-ROP threat model. Our results also show that the locations of leaked pointers used in JIT-ROP attacks have no impacts on gadget availability, suggesting high pointer-based connectivity among code pages.

I. INTRODUCTION

Just-in-time return-oriented programming (JIT-ROP) (e.g., [75]) is a powerful attack technique that enables one to reuse code even under fine-grained address space layout randomization (ASLR). Fine-grained ASLR, also known as fine-grained code diversification or randomization, reorders and relocates program elements. Fine-grained randomization would defeat conventional ROP code reuse attacks [72], as the attacker no longer has direct access to the code pages of the victim program and its libraries. In other words, a leaked pointer only unlocks a small portion of the code region under fine-grained code randomization, seriously limiting the attack’s ability to harvest code for ROP gadget purposes.

JIT-ROP attacks have the ability to discover new code pages dynamically [74], by leveraging control-flow transfer instructions, such as call and jmp. Under fine-grained code randomization, the execution of a JIT-ROP attack is complex, as code page discovery has to be performed at runtime. From the defense perspective, re-randomization techniques (TASR [8], Shuffler [86], Remix [20], CodeArmor [18], RuntimeASLR [80], Stabilizer [26], etc.) have the potential to defeat JIT-ROP attacks. Re-randomization techniques continuously shuffle the address space at runtime. This continuous shuffling breaks the runtime code discovery process by making the already discovered code pages obsolete. However, the interval between two consecutive randomizations must satisfy both performance and security guarantees.

Quantitative evaluation of how code (re-)randomization impacts code reuse attacks, e.g., in terms of interval choices, gadget availability and Turing completeness property of gadgets has not been reported. In ROP literature, Turing completeness refers to a set of gadgets that cover the Turing-complete operations including memory, assignment, arithmetic, logic, control flow, function call, and system call [65].

Some (re-)randomization techniques can make it difficult for current gadget finding techniques to discover all gadgets. Thus, in-depth and systematic measurement is necessary, which can provide new insights on the impact of code (re-)randomization on various attack elements, such as code pointer leakage, Turing completeness property, and gadget chain formation.

It is also important to investigate how to systematically compute an effective re-randomization interval. Current re-randomization literature does not provide a concrete methodology for experimentally determining an upper bound of re-randomization intervals. Shorter intervals (e.g., millisecond-level) incur performance or runtime overhead whereas longer intervals (e.g., second-level) give attackers more time to launch exploits. An upper bound would help guide defenders to make informed re-randomization interval choices.

We report our experimental findings on code pointer leakage, gadget availability, Turing completeness property, and gadget chain formation, under fine-grained ASLR and re-randomization tools including Zipr [38] and Shuffler [86]. Our evaluation involves up to 13 applications and 19 dynamic libraries. We aim to experimentally answer the following research questions (RQs).

RQ #1: How does fine-grained code (re-)randomization quantitatively impact on the availability of various kinds of gadgets that are essential for the completeness of JIT-ROP payloads?

RQ #2: How does the location of a code pointer leak impact on the availability of gadgets under fine-grained code randomization?
RQ #3: How does fine-grained code randomization impact the quality of a gadget chain (i.e., payload)?

We designed a measurement mechanism that allows us to perform JIT-ROP’s code page discovery in a scalable fashion. This mechanism enables us to compare results from a number of programs and libraries under multiple ASLR conditions (coarse-grained, fine-grained function level, fine-grained basic block level, fine-grained instruction, and register levels).

Our key experimental findings and technical contributions are summarized as follows.

- We provide a methodology to compute the upper bound for re-randomization intervals. We compute the upper bound $T$ by measuring the minimum time for an attacker to find a Turing-complete set of JIT-ROP gadgets. In other words, if the re-randomization interval is less than $T$, then a JIT-ROP attacker is unable to obtain a Turing complete gadget set. Our experiments show that this upper bound ranges from 4 seconds to 17 seconds for various applications (with dynamic libraries).

In addition, we present a general methodology for quantifying the number of JIT-ROP gadgets. For fine-grained single-round randomization, our results show that an instruction-level solution (namely Zipr [38]) limits the availability of gadgets up to 90% and successfully breaks the Turing completeness of JIT-ROP payloads. We also observe that fine-grained randomization slightly degrades the gadget quality, in terms of register-level corruption.

- Our experiments show that locations do not have any impact (i.e., zero standard deviations) on the reachability from one code page to another. Every code pointer leak is equally viable for derandomizing address space layout. A pointer leakage in any location allows attackers to obtain a basic set of gadgets.

A stack has a higher risk of revealing dynamic libraries than a heap or data segment because our experiments show that stacks contain 16 more libc pointers than heaps or data segments on average. This finding indicates the necessity of randomizing stack over heap or global variables.

- From the perspective of defense, our findings suggest that code isolation and reducing semantic code connectivity are important for defending against JIT-ROP attacks. As instruction-level reordering breaks up gadgets, current gadget finding and chaining techniques are no longer effective. Thus, from the perspective of understanding attack capabilities, redefining traditional ROP gadgets into smaller (i.e., one line) building blocks and demonstrating new gadget chain compilers would be interesting. Our results suggest that gadgets quantity and quality vary with runs. Thus, how to make attacks more reliable and robust in practice is also an interesting direction.

Besides the comprehensive measurement work, we distill common attack operations in existing ASLR-bypassing ROP attacks (e.g., [10], [15], [28], [75]) and present a generalized attack workflow that captures the tasks and goals. This workflow is useful beyond the specific measurement study.

II. THREAT MODEL AND DEFINITIONS

Coarse-grained ASLR (or traditionally known as only ASLR [81]) randomly relocates shared libraries, stack, and heap, but does not effectively relocate the main executable of a process. This defense only ensures the relocation of the base address of a segment or module. The internal layout of a segment of the module remains unchanged. The Position Independent Executable (PIE) option allows the main executable to be run as position independent code, i.e., PIE relocates the code and data segments. For comparison purposes, we performed experiments on coarse-grained ASLR with PIE enabled on a 64-bit Linux system.

Fine-grained ASLR, aka fine-grained code randomization or code diversification, attempts to relocate all the segments of the main executable of a process, including shared libraries, heap, stack, and memory-mapped regions and restructures the internal layouts of these segments. The granularity of the randomization varies, e.g., at the level of functions [22], [35], [45], basic blocks [20], [46], [84], instructions [40], or machine registers [41]. We evaluated Zipr [38], Selfrandoo [SR] [22], Compiler-assisted Code Randomization(CCR) [40], and Multicompile(MCR) [41]. We also evaluated Shuffler [56], a re-randomization tool. We are unable to test other tools due to various robustness and availability issues.

We assume standard defenses such as W+X and RELRO are enabled. W+X specifies that no address in a process’ address space is writable and executable at the same time. RELRO stands for Relocation Read Only. It ensures that the Global Offset Table (GOT) entries are read-only. RELRO is a compiler flag and full RELRO is now by default deployed on mainstream Linux distributions.

In addition, our experimental evaluation is conducted under the following assumptions. Attackers do not have any prior knowledge of the target application’s memory layout, i.e., attackers have to derandomize the layout through an attack.

Fine-grained code randomization is applied in every executable and associated library in a target system (unless specified otherwise). Similar to JIT-ROP [75], we assume that no code pointer protection [7], [23], [31], [48], [49], [51], [53] exists in the target application. We discuss the need for measuring code pointer protection solutions under the JIT-ROP model in Section VII. We assume that memory permission-related protections such as XnR [5], NEAR [85], Readaactor [24] and destructive read-related protections such as Heisenbyte [80], etc. are not present in the victim machine. We assume attackers have already obtained a leaked code pointer (e.g., a function pointer or a virtual table pointer) through remote exploitation of an application/library vulnerability. Such an assumption is standard in existing attack demonstrations.

Next, we define the terms of Turing completeness, upper bound of re-randomization intervals, minimum footprint gadgets, and extended footprint gadgets.

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1. https://git.zephyr-software.com/opensrc/rdi-proj-examples
2. https://github.com/immunant/selfrandoo
3. https://github.com/kevinlee001/CCR
4. https://github.com/securesystemslib/multi-compiler
5. Attacks (e.g., AOCR [60] and code inference [76]) are still possible with those defenses.
Definition 1: Turing completeness refers to the availability of a set of gadgets that covers the Turing-complete operations including memory operations (i.e., load memory LM and store memory SM gadgets), assignments (i.e., load register LR and move register MR gadgets), arithmetic operations (i.e., arithmetic AM, arithmetic load AM-LD, and arithmetic store AM-ST gadgets), logical operations (i.e., logical gadgets), control flow (i.e., jump JMP gadgets), function calls (i.e., CALL gadgets), and system calls (i.e., SYSTEM SYS gadgets) \[^{[65]}\].

Definition 2: The upper bound \( T^A_X \) of a re-randomization scheme \( \mathcal{P} \) under a JIT-ROP attacker \( A \) is the maximum amount of time between two consecutive randomization rounds that prevent \( A \) from obtaining a set of Turing-complete gadgets, i.e., for any interval \( T^A_X < T^A_P \), the set of gadgets obtained under \( T^A_P \) cannot cover all the Turing-complete gadgets.

Our security definition of the upper bound in Definition \(^2\) is specific to the JIT-ROP threat, and is not applicable to other threats (e.g., side-channel threats). A shorter interval may still allow attackers to gain information. However, as our Section \(^{III}\) shows, without gadgets that information may not be sufficient for launching exploits.

Extended footprint (EX-FP) gadgets: Turing-complete gadgets (i.e., load, store, assignment, etc.) and attack-specific gadgets (e.g., reflector gadget, call site gadget, etc.) are useful for arbitrary computation and building an attack payload. A gadget is an extended footprint gadget if it is an instance of the set of Turing-complete or attack-specific gadgets. An EX-FP gadget may contain additional instructions that may cause side effects in an attack payload.

Minimum footprint (MIN-FP) gadgets: A minimum footprint gadget is also an instance of the set of Turing-complete or attack-specific gadget, but it does not cause any side effect in an attack payload.

III. COMPARISON OF JIT-ROP AND BASIC ROP ATTACKS

We manually analyze a number of advanced attacks to extract common attack elements and identify unique requirements. We illustrate the key technical differences between JIT-ROP and conventional (or basic) ROP attacks. This Section helps one understand our experimental design in Section \(^{IV}\) and findings in Section \(^{V}\) We analyze various attack demonstrations with a focus on attacks (e.g., \(^{[10]}\), \(^{[15]}\), \(^{[28]}\), \(^{[75]}\)) in our threat model.

To overcome both coarse- and fine-grained ASLR and conduct an attack to gain privileged operations, an attacker needs to perform the tasks presented in Figure \(^1\). The attack workflow has three major components: memory layout derandomization, system access, and payload generation. We describe each component in Sections \(^{II-A}\), \(^{II-B}\) and \(^{II-C}\) respectively.

- Memory layout derandomization: Due to the W\(\oplus\)X defense, attackers must reuse code (via gadgets) in their attacks. Attackers need to derandomize the memory layout to discover gadgets (steps \(^{2}\)-\(^{4}\) for JIT-ROP and steps \(^{2}\) and \(^{4}\) for basic ROP in Figure \(^1\)). Usually, attackers leverage memory corruption vulnerabilities to leak memory content \(^{[78]}\) and start the derandomization process utilizing the leaked memory.
- System access: Attackers access privileged system operations by issuing system APIs or gadgets. However, useful attacker actions may also include reading user data (such as email) or stealing authentication tokens (like cookies). These actions do not involve system calls. In this paper, we only consider those attacks that utilize system calls. Attackers invoke system calls through syscall gadgets. One can find syscall gadgets through step \(^{4}\) in JIT-ROP along with other gadgets. In basic ROP, one must find the syscall gadgets through pointer leakage in system libraries (like libc) or application binaries (step \(^{9}\)).
- Payload generation: Attackers generate payloads by putting many pieces (e.g., gadgets, functions, constants, strings, etc.) together. This process must ensure a setup for calling system functions or system gadgets. Steps \(^{5}\) and \(^{7}\) in Figure \(^1\) correspond to the payload generation operation for JIT-ROP and basic-ROP, respectively. The target of a payload is to achieve an attack goal, e.g., memory leak, launching a malicious application, or launching a root shell.

A. Memory Layout Derandomization

Derandomizing the fine-grained address space layout is the key for mounting code-reuse attacks with gadgets. This step requires overcoming several obstacles.

Memory disclosure. The most common way of derandomizing memory layout is through a memory disclosure vulnerability in an application. Attackers use vulnerabilities in an application’s memory (e.g., heap overflows, use-after-free, type confusion, etc.) and weaknesses in system internals (e.g., vulnerabilities in the glibc malloc implementation or its variants \(^{[5]}\), \(^{[39]}\), Heap Feng Shui \(^{[77]}\), Flip Feng Shui \(^{[64]}\)) to leak memory contents (Steps \(^{2}\) and \(^{4}\)). Details on memory corruption model can be found in \(^{[34]}\), \(^{[79]}\) and an example in \(^{[78]}\).

Code reuse. Due to W\(\oplus\)X defense, adversaries cannot inject code in their payload. Return-oriented programming (ROP) \(^{[72]}\) and its variants jump-oriented programming (JOP) \(^{[12]}\) and call-oriented programming (COP) \(^{[35]}\) can defeat this defense. These techniques use short instruction sequences (i.e., gadget) from the code segments of a process’ address space and allow an adversary to perform arbitrary computations. ROP tutorials can be found in \(^{[27]}\), \(^{[75]}\). The difference between basic ROP \(^{[72]}\) and JIT-ROP \(^{[75]}\) is described next.

Basic ROP. Coarse-grained ASLR only randomizes the base addresses of various segments and modules of a process. The content of the segments and modules remains unchanged. Thus, it is feasible for an adversary to launch a basic ROP attack \(^{[2]}\) using gadgets given a leaked address from the code segment of interest. The adversary only needs to adjust the addresses of pre-computed gadgets w.r.t. the leaked address. Step \(^{4}\) in Figure \(^1\) is about this task.

Just-in-time ROP. Fine-grained ASLR randomizes the base addresses, as well as the internal structures of various segments and modules of a process. Thus, simply adjusting the addresses of pre-computed gadgets as in the basic ROP no longer works. An adversary needs to find gadgets dynamically at the time of an exploit. She may attempt to scan the process address space
in order to search for gadgets. However, this linear scanning may lead to a segmentation fault and crash the process. A powerful technique introduced by JIT-ROP [75] is code page harvest, which is explained next.

JIT-ROP attacks exploit the connectivity of code in memory to derandomize and locate instructions. The **code harvest process** in JIT-ROP identifies gadgets at runtime by reading and disassembling the text segment of a process. This process starts with computing the page number of a disclosed code pointer at runtime. A 64-bit system uses the first 52 bits for page numbers if the page size is 4K. Once the page number is computed, the process reads the entire 4K data of that page. A light-weight disassembler converts the page data into instructions. The code harvest process searches for chain instructions, such as `call` or `jmp` instructions to find pointers to other code pages.

An illustration is shown in Figure 2. The code harvest process starts from the disclosed pointer (0x11F95C4), reads 4K page data (0x11F9000-0x11F9FFF), disassembles the data, searches for `call` and `jmp` instructions to find other pointers (0x11FB410 and 0x11FCFF4) to jump to those code pages. This process is recursive and stops when all the reachable code pages are discovered. We implemented this code harvesting method for our evaluation. It is important to mention that indirect calls to library functions can also be resolved to jump to the library code pages.

**Code page harvest and gadget identification.** In step 3, an adversary utilizes the leaked memory address to read code pages of the process’ code segments. In step 4, she can identify and create gadgets by disassembling the read code pages. She can scan for byte values corresponding to `ret` opcodes (e.g., 0xC2, 0xC3) and perform a narrow-scoped backward disassembly from there. She also can use an improved disassembler (e.g., Capstone [13]) to perform gadget identification. The adversary performs step 3 and 4 repeatedly until she finds enough gadgets for her exploit.

**B. System Access**

If the execute-only defenses (e.g., XnR [6], NEAR [85], Readactor [24] and Heisenbyte [80]) and CFI (e.g., CCFIR [88] and bin-CFI [89]) are not enforced, adversaries do not need to invoke the entire functions to ensure legitimate control flow. An adversary can just chain together enough gadgets for setting up the arguments of a system call and invoking it. This observation is particularly true for Linux, which is the focus of this paper. In Windows exploits [75], the approach is slightly different, as adversaries commonly invoke a system API instead of invoking a system call directly. **Syscall gadgets** can be found in an application’s code or dynamic library. For basicROP attacks, attackers can adjust pre-computed system gadgets from dynamic libraries, given that she manages to obtain a code pointer from a dynamic library (e.g., libc). Step 9 in Figure 1 is for this task. This task is performed manually and offline. The attacker may obtain the library code pointer from an application’s stack or heap or data segment.

**C. Payload Generation**

Once an adversary derandomizes the memory layout of a process and gets access to enough gadgets, she glues different parts (e.g., gadgets, functions, strings, constants, etc.) together to build a payload or attack chain. The adversary may generate the payload dynamically at step 5 in the presence of fine-grained code randomization or manually at step 5' in the presence of coarse-grained code randomization and stores the payload in a stack. Because a payload is primarily a set of addresses that point to some existing code in an application’s address space, attacks do not execute anything stored in a stack/heap, which is protected by W⊕X. The adversary may utilize the same vulnerability as in step 2 or a different vulnerability to hijack a program’s control flow at step 6 to redirect the flow to the stored payload.

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which restricts “gadgets” to only legitimately called functions
It is desirable for attackers to obtain attack chains that have minimal side effects, i.e., having a payload that fulfills attack goals without generating any unnecessary computation. However, this property may not be guaranteed if the gadget availability is limited by code randomization. We refer to the side effect of gadgets as footprints. We defined the minimum footprint gadget and extended footprint gadget in Section II.

For ROP attacks (e.g., [15]) that bypass control-flow integrity (CFI) defenses, the attackers also need to prepare specialized payloads in addition to the previous tasks. For example, the Flashing (FS) and Terminal (TM) gadgets in Table VII in the Appendix were designed by Carlini and Wagner [15] to bypass specific CFI implementations (namely, kBouncer [60] and ROPEcker [21]).

IV. EXPERIMENTAL DESIGN

We describe our measurement methodologies for evaluating fine-grained ASLR’s impact on the memory layout derandomization, system API access, and payload generation of JIT-ROP.

One major challenge is how to quantify the impact of fine-grained code randomization or re-randomization. Our approach is to count the number of NOP gadgets that are available to attackers under the JIT-ROP code harvesting mechanism. Another challenge is how to quantify i) the difficulty of accessing internal system functions and ii) the quality of gadget chains. For the former, our approach is to compute the number of system gadgets and libc pointers in a stack or heap or data-segment of an application. In order to quantify the quality of gadget chains, we design a register-level measurement heuristic to compute the register corruption rate.

A. Measurement Methodologies

Measurement Methodology for Memory Layout Derandomization. This methodology is for evaluating RQs #1, #2, and #3. We manually extract 19 types of gadgets from various attacks [10], [14], [15], [46], [25]. These gadget types include load memory (LM), store memory (SM), load register (LR), move register (MR), arithmetic (AM), arithmetic load (AM-LD), arithmetic store (AM-ST), logic, jump (JMP), call (CALL), system call (SYS), and stack pivoting (SP) gadgets. In addition to these, the gadget types also include some attack-specific gadgets such as call preceding (CP), reflect (RF), call site (CS2) and entry point (EP) gadgets. Table VII in the Appendix shows those gadget types in more details.

These 19 types of gadgets include the Turing-complete set of gadgets (see Definition I). The Turing-complete tools and some attack-specific gadgets (e.g., CP, RF, CS2, and EP) are appropriate for our evaluation because we can precisely identify those gadgets. Some attack specific gadgets such as CS1 and FS are very application-specific. They do not have any concrete forms or concrete attack goals. These gadgets are used to trick defense mechanisms. We also attempt to evaluate the block-oriented gadgets used for Block-Oriented Programming (BOP) [43].

In our experiments, we measure the occurrences of these gadgets under fine-grained code randomization and re-randomization. For code re-randomization, we attempted to use six re-randomization tools. However, some of the tools are unavailable and some have runtime and compile-time issues. In the end, we were able to obtain only Shuffler [86]. For code randomization, we used four relatively new code randomization tools: Zipr [38], SR [22], CCR [40], and MCR [41], because of their reliability. Table I shows the key differences between these randomization schemes.

We compile and build a coarse-grained and a fine-grained version of each application or dynamic library for each run using each of the four randomization tools, i.e., each run has a different randomized code. For Shuffler [86], we do not need to prepare special binaries. We use ropper [67], an offline gadget finder tool, under coarse-grained ASLR. Under fine-grained ASLR, we recreate the JIT-ROP [75] exploitation process, including code page discovery and gadget mining. We use the capstone [13] disassembler for disassembling a code page.

We write a tool to search for gadgets of a specific type. We scan the opcodes of ret (0xC3) and ret xxx (0xC2) and perform a narrow-scoped backward disassembly from those locations to collect ROP gadgets. Similarly, we scan the opcodes of int 0x80 (0xCD 0x80), syscall (0x0F 0x05), syscall (0x0F 0x34) and call gs:[0x10] (0x65 xPF 0x15 0x10 0x00 0x00 0x00) for system gadgets.

Measurement Methodology for System Access. We measure the difficulty of accessing privileged operations through the availability of system gadgets and vulnerable library pointers in a stack, heap or data-segment. For system gadgets, we compare the number of system call gadgets under the coarse- and fine-grained code randomization and compute the reduction in the gadget quantity. For the measurement of vulnerable pointers in a stack/heap/data-segment, we examine the overall risk associated with a stack/heap/data-segment by identifying the number of unique libc pointers in that stack/heap/data-segment. For the evaluation purpose, we do not try to exploit vulnerabilities to leak libc pointers from the stack/heap/data-segment, rather we assume that we know the address mapping of the libc library and can find the libc pointers through a linear scanning of the stack/heap/data-segment. We discuss the existence of libc pointers in popular applications in Section V-D.

Fig. 3: Instruction location randomization. This figure is adopted from ILR [40].
TABLE I: The key differences in the various randomization and re-randomization schemes evaluated.

| Tools   | Randomization Scheme(s) | Randomization Time | Compiler Assistance Required | Techniques                                                                 | Performance Overhead |
|---------|-------------------------|--------------------|------------------------------|----------------------------------------------------------------------------|----------------------|
| Shuffler [86] | Function-level re-randomization | Runtime            | No                           | - Loads itself as a userspace program<br>- Contains a separate thread for shuffling the functions continuously<br>- Represents code pointers as indices for flexibility | 14.9% [86]          |
| Zipr [38]      | Instruction-level randomization | Static rewriting   | No                           | - Reorders all instructions and generates ILR static rewrite rules<br>- Executes randomly scatter instructions using a process-level virtual machine (PVM) utilizing static rewrite rules or a fallback through map<br>- Keeps the same layout unless rewrite again | <5% [38]            |
| SR [22]        | Function-level randomization | Load time reorder  | No                           | - Adds a linker wrapper that intercepts calls to the linker and asks the selfrando library to extract the necessary information to reorder functions<br>- Reorders functions once a binary loaded into memory<br>- Reorders on each load | <1% [22]           |
| MCR [41]       | Function- and register-level randomization | Link time reorder  | Yes                          | - Reorders functions and machine registers during link time optimization<br>- Keeps the same layout unless compiled and built again | 1% [41]             |
| CCR [46]       | Function and block-level randomization | Installation time  | Yes                          | - Extracts metadata during compilation<br>- Reorders functions and basic-blocks based on the metadata<br>- Keeps the same layout unless rerandomized again | 0.28% [46]          |

Measurement Methodology for Payload Generation. We evaluate our RQ #3 (in Section V.C) using this methodology. We focus on measuring the quality of individual gadgets to approximate the quality of a gadget chain. The quality of a set of gadgets for generating payloads is essential, as attackers need to use gadgets to set up and prepare register states. To measure the quality of individual gadgets, we perform a register corruption analysis for each gadget, which is briefly described next. The detail description of our register corruption analysis is in Appendix A.

Typically, a gadget contains one core instruction that serves the purpose of that gadget. For example, an MR gadget may contain mov eax, edx as the core instruction and some additional instructions before/after the core instruction. We measure the register corruption rate by analyzing how the core instruction of a gadget can get modified by those additional instructions. A core instruction may be modified by i) the instruction(s) before the core instruction, ii) the instruction(s) after the core instruction, and iii) both the instruction(s) before/after the core instruction. For each gadget, we consider these three scenarios and determine whether the gadget is corrupted or not.

Next, we discuss the code randomization and re-randomization tools briefly in the following paragraphs.

Shuffler [86] runs itself alongside the userspace program that it aims to protect. It has a separate asynchronous thread that continuously permutes all the functions to make any memory leaks unusable as fast as possible.

Zipr [38] reorders the location of each instruction in an executable or library (Figure 3). Zipr works directly on binaries or libraries with no compiler support. Zipr [38] is based on the Intermediate Representation Database (IRDB) code. Zipr shuffles code during the rewriting process, which is called block-level instruction layout randomization.

Selfrando (SR) [22] applies code diversification at the load time. This tool collects Translation and Protection (TraP) information, a minimal set of metadata for function boundaries during the linking phase. This tool also inserts a dynamic library called libselfrando. At the load time, this library takes control of the execution, reorders the position of each function in an executable utilizing the TraP information, and relinquishes the control to the original entry point of the executable. SR can use either GCC or Clang as its compilation engine.

Multicompiler (MCR) [41] applies the code diversification at the link time. This tool randomizes functions, machine registers, stack-layout, global symbols, VTable, PLT entries, and contents of the data section. The tool also supports padding such as NOP insertion, global padding, and insertion of padding between stack frames. We choose the function and machine register level randomization for our evaluation. MCR uses the clang-3.8 LLVM compiler as its compilation engine.

Compiler-Assisted Code Randomization (CCR) [46] applies the code diversification at the installation time, i.e., rewrites an executable binary after reordering the functions and basic blocks of the executable. This tool collects metadata for code layout, block boundaries (i.e., the basic block boundaries, functional block boundaries, and object block boundaries), fixup, and jump table of an executable during compilation and linking phases. The tool embeds this metadata into the executable by adding a new section called .rand. A Python script then rewrites the executable binary by reordering the positions of basic blocks and functional blocks. CCR uses the clang-3.9 LLVM compiler as its compilation engine.

Availability and robustness of fine-grained ASLR tools. We found that the majority of code diversification implementations, including ASR [35], ASLP [45], Remix [20], and STIR [84], are not publicly available. Some available tools (e.g., MCR [41], CCR [46] and SR [22]) operate on the source code level. They require the recomposition of source code including dynamic libraries. We experienced multiple linking issues while using CCR and SR to compile Glibc code. The tool authors confirmed the limitations (discussed in Section VI). ORP [61] was the randomization tool used in Snow et al.’s JIT-ROP demonstration [75]. It operates on Windows binaries, incompatible with our setup.

V. EVALUATION RESULTS AND INSIGHTS

Experimental setup. All experiments are performed on a Linux machine with Ubuntu 16.04 LTS 64-bit operating system.
We write several Python and bash scripts for automating our analysis and measurement process. The scripts have around 3,500 lines of code including around 2,000 lines of Python code on top of GDB-Python-Utils [4]. We use the Python regular expression library re for finding semantically different gadgets, e.g., the Turing-complete gadgets and attack-specific gadgets. To overcome the issues involved with JIT-ROP [75] for searching gadgets on the fly at runtime, we run/load each application/library and attack the application/library to GDB. The Python scripts are also loadable in GDB. This setup allows us to avoid a process’ memory mapping related complexities. We also plan to make our analysis tool and data available to the public.

We perform our experiments on the latest and stable versions of bzip2, cherokee, hiawatha, httpd, lighttpd, mupdf, nginx, openssl, proftpd, sqlite, openssh, thttpd, tor, and xpdf. We also perform our experiments on dynamic libraries. Dynamic libraries include libcrypto, libgmp, libhogweed, libxml2, libgcrypt, libgnuts, libgpg-error, libtasn1, libz, libnettle, libopenjp2, libopenlibm, libpng16, libtomcrypt, libunistring, and libxml2. We select these applications or dynamic libraries by considering the fact that many attackers demonstrate their attacks on most of these applications or libraries. Besides, these applications/libraries include a diverse set of areas such as the server area, PDF reader, cryptography, networking utility, database, browser, math library, image library, and system library. Table II shows the numbers of applications/libraries used for evaluating Shuffler [86], Zipr [38], SR [22], CCR [46], and MCR [41]. Each tool evaluates a different set of applications and libraries because no tool is capable of (re-)randomizing all of our selected applications (13 in total) and libraries (19 in total). However, we also evaluate these tools using the common set of applications and libraries that these tools can randomize.

To evaluate Shuffler [86], we take 100 consecutive address space snapshots from an application/library re-randomized by Shuffler [86]. Then, we manually analyze the address space snapshots. We manually compile (or rewrite the executables of) these programs to enforce fine-grained code randomization up to function level using SR [22], basic block level using CCR [46], both functional and register levels using MCR [41], and instruction level using Zipr [38]. We use LLVM Clang version 3.9.0, version 3.8.0 and GCC version 5.4.0 as the compilers for CCR, MCR and SR, respectively (as required). We run, load or rewrite each application or dynamic library 100 times to reduce the impact of variability on the number of gadgets in each run or load.

A. Impact on the Availability of Gadgets

RQ #1: How does fine-grained code (re-)randomization quantitatively impact on the availability of gadgets? Does it break the Turing completeness?

We measure a total of 13 types of gadgets, including 11 gadgets for Turing-complete operations and 2 attack specific gadgets from various attack demonstrations [10], [15], [33], [36], [65], [75]. We measure the set of gadgets that are required for Turing-complete operations defined in Definition 1. For partial Turing-complete gadgets, we measure the percentage of Turing-complete gadgets. Partial Turing-complete gadgets have gadgets to perform some Turing-complete operations, but not all. For example, 50% of Turing-complete gadgets means that the gadgets can perform 50% of the Turing-complete operations. We identify 11 types of gadgets necessary for seven Turing-complete operations. Any type of gadgets missing from the 11 types of gadgets makes the Turing-complete gadgets partial. We check the existence of these 11 types of gadgets and calculate the percentage of Turing-complete gadgets.

1) Impact of Re-randomization: We assess the impact of different re-randomization intervals on the availability of Turing-complete gadgets. We run the Nginx server and re-randomize the Nginx’s address space with a re-randomization interval of 30 seconds. We take 100 snapshots of Nginx’s address space for 100 consecutive re-randomizations. We identify the number of minimum and extended footprint gadgets from each snapshot. We calculate the average number of minimum and extended footprint gadgets for each snapshot.

To measure the upper bound for re-randomization intervals and assess the impact of different re-randomization intervals on the availability of Turing-complete gadgets, we run dynamic code harvesting process for 12 applications including 15 libraries such as libc, libcrypt, libpcre, libz, libcrypto, libgnuts, etc. For each application, we record the time at the start of the code page harvesting process, after each code page harvest, and the completion of the code page harvesting process. We also measure the number of Turing-complete gadget types that the code harvesting process covered so far while recording the time. Figure 4 shows the percentages of discovered Turing-complete gadgets for different re-randomization intervals.

Figure 4 shows that as the re-randomization interval increases, the percentages of the Turing-complete gadgets also increase. Longer intervals help attackers reveal more Turing-complete gadgets than shorter intervals. However, longer intervals may not immediately help attackers reveal more Turing-complete gadgets. For example, we notice some flat lines of several seconds for some applications such as mupdf (∼4s), hiawatha (∼4s), proftpd (∼7s), thttpd (∼9s), and cherokee (∼11s). The flat lines indicate that the percentage of Turing-complete gadgets does not increase with the increase of the intervals within the duration of those flat lines. Most flat lines also indicate that one or two missing gadget types prevent the set from reaching Turing completeness. That is, one or two types of gadgets are very scarce. The most scarce gadgets are Load-Memory (LR) and Arithmetic-Load (AM-LD). For example, the gadget discovery process searches for the Load-Memory (LR) gadgets for around 7 seconds for proftpd. The fundamental reason for the scarcity is that some applications (including libraries) do not have pure register-based memory access. The memory accesses are made by adding some offsets to the registers.

Clearly, the value of the upper bound for the re-

| Tool      | Applications (13 Total) | Libraries (19 Total) |
|-----------|-------------------------|----------------------|
| Shuffler  | 12                      | 15                   |
| Zipr [38] | 9                       | 9                    |
| SR [22]   | 11                      | 15                   |
| MCR [41]  | 8                       | 8                    |
| CCR [46]  | 9                       | 9                    |

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Clearly, the value of the upper bound for the re-
randomization interval depends on the machine (e.g., CPUs, cache size, memory, etc.) where the measurement is conducted. Figure 4 shows that the lowest re-randomization interval to achieve 100% of Turing-complete gadgets is around 4 seconds in our experiments. The number is computed by taking the lowest value that is observed across the 11 applications (with the associated dynamic libraries) in Figure 4 to achieve the Turing-complete gadget set. We choose the lowest value to ensure security guarantees. Using our methodology, defenders can perform the measurement on their machines to help determine what interval is appropriate, while satisfying overhead constraints.

We also notice that 8 applications achieve ~60% of Turing-complete gadgets within 1.0~1.5 seconds. This observation indicates the necessity of the relevance analysis of partial Turing-complete gadgets in the context of attack goals. For example, partial Turing-complete gadget set could be useful for some attack scenarios where attackers do not need the system call gadgets. Thus, defenders need to determine to what extent partial gadgets are useful and set the re-randomization interval accordingly. In our experiments, we conservatively consider only the 100% of Turing-complete gadgets to compute the upper bound of re-randomization intervals. We leave the relevance analysis of partial-gadgets in the context of attack goals as a future research direction. In Section VI we discuss the implications of these results in real-world operations, e.g., how to choose re-randomization intervals for performance- and security-critical applications.

2) Impact of Single-round Randomization: Table III summarizes the impact of fine-grained code randomization on the availability of gadgets in various applications (i.e., the main executables) and dynamic libraries. We measure the numbers of the various gadgets (as mentioned above) for each application and library before and after randomizing with the four randomization tools (i.e., Zipr [38], SR [22], MCR [41], and CCR [46]). Each application or library is run/loaded in memory for 100 times after randomizing 100 times when necessary. The numbers of gadgets are averaged over 100 runs/loads of an application or library. Then the numbers of gadgets are averaged over the number of applications and libraries for each randomization tool. Table III shows the overall gadget reductions in application and library categories for Zipr [38], SR [22], MCR [41], and CCR [46].

On average, the amount of gadgets is reduced (by 27%~39% for minimum footprint and 34%~38% for extended footprint gadgets) when applications are randomized using SR, CCR, and MCR. For dynamic libraries, the reductions range from around 6% to 24% for minimum footprint gadgets and around 33% to 38% for extended footprint gadgets. However, Zipr [38] reduces the overall gadget amount significantly by around 80%~90% for both minimum and extended footprint gadgets. Table III also shows the reduction of gadgets in seven Turing-complete (TC) categories and indicates whether the Turing completeness is preserved after applying the code randomization. The numbers before and after a vertical bar (|) indicate the reduction of minimum and extended footprint gadgets for a Turing-complete category. Since the number of applications or libraries is different for each randomization tool in Table III, we also use the common set of applications and libraries to validate the results shown in Table III. Figure 8 in the Appendix shows the validation results. According to the results, all the tools exhibit similar reduction while we evaluate them using the common set of applications and libraries.

The Turing completeness is preserved in the randomized versions of applications or libraries when randomized by SR, MCR, and CCR. The Turing completeness is also preserved for both minimum and extended footprint gadgets. However, Zipr destroys the Turing completeness property for minimum footprint gadgets. Turing completeness is broken when there is no gadget in one of the Turing-complete categories. For example, in Table III the reduction of minimum footprint

Fig. 4: Changes of the percentage of Turing-complete gadgets with re-randomization intervals. The percentage of Turing-complete gadgets (Y-axis) of an application is computed based on the number of distinct Turing-complete gadgets across the 11 types of Turing-complete gadgets described in Definition 1. Turing-complete gadgets include the gadgets from the associated dynamic libraries as well as the application’s main executable.

Compiling once and running 100 times is enough for SR. 100 times diversification, 100 times compilation, and 100 times rewriting are required for CCR, MCR, and Zipr, respectively.
TABLE III: Impact of fine-grained single-round randomization on the availability of gadgets in various applications and dynamic libraries. The data in each row of SR [22] is generated by averaging the data of 11 applications and 15 dynamic libraries. The data in each row of Zipr [38] and CCR [46] is generated by averaging 9 applications and 9 libraries for each tool. 8 applications and 8 dynamic libraries are used for MCR [41]. The data of each application or library is the average result of 100 runs/loads/rewrites. The standard deviations vary between 0.3∼3.4 for minimum footprint and 5.04∼22.85 for extended footprint gadgets. ↓ indicates reduction.

| Tools  | Granularity | MIN-FP | EX-FP | Memory | Assignment | Arithmetic | Logical | Control | Function | System | Call | Preserved? |
|--------|-------------|--------|-------|--------|-----------|-----------|---------|---------|----------|--------|------|------------|
| Zipr   | Inst.       | 80.91  | 88.45 | 100    | 93.5      | 61.9      | 91.5    | 100     | 86.3     | 57.5   | 82.1 | 66.0       | 88.7 | 73.1 | 92.5 | 83.33 | 0 | ✗* |
| SR     | FB          | 40.28  | 36.53 | 3.6    | 21.0      | 10.8      | 42.9    | 14.7    | 9.8      | 35.5   | 36.2 | 23.4 | 29.3 | 25.0 | 48.4 | 0 | 0 | ✓ |
| MCR FF | Reg.        | 37.19  | 34.81 | -16.7  | 25.6      | -4.4      | 23.0    | 22.0    | 38.8     | 2.4    | 28.8 | 40.5 | 59.2 | 14.0 | 63.7 | 80.0 | 0 | ✓ |
| CCR BB |            | 27.02  | 38.77 | 2.3    | 31.7      | 4.4       | 41.2    | 12.2    | 4.8      | 24.4   | 26.4 | 56.0 | 71.2 | 30.9 | 61.4 | 0 | 0 | ✓ |

* For Zipr, TC is not preserved for minimum footprint gadgets, but TC is preserved for extended footprint gadgets.

The reductions for libraries in the two categories (i.e., memory and arithmetic) are 94.4% and 96.8%, respectively. These two reductions are not 100% because some libraries contain a few gadgets (a total of 4 for memory and 3 for arithmetic). When the numbers of gadgets are averaged over the number of libraries, the average value becomes close to zero.

Most of the applications and libraries do not contain any syscall gadgets (as expected) because applications and libraries usually make syscalls through libc. However, applications or libraries may have occasional use of the syscall function. For example, the log_tid() function is the only one of httpd that invokes syscall function. Similarly, other applications or libraries occasionally invoke the syscall function. This is why the number of syscall gadgets is low in most cases. Since SR is only able to randomize a light-weight version of libc (musl), we see slightly high values for system gadgets in Table III for SR.

We also assess the availability of Turing-complete gadgets under a single randomization pass of Shuffler [86]. On average, we observe a 24% reduction in minimum footprint gadgets and 3% reduction in extended footprint gadgets compared to the non-randomized version of Nginx. Reduction means that the re-randomization technique prevents the current gadget finding tools from obtaining gadgets from an application’s address space. The low reductions are expected, as Shuffler’s security relies on the capability of continuously shuffling code locations, not a single randomization pass.

3) Reasons Behind Gadget Changes: Ideally, function or basic block randomization should not destroy gadgets because the gadget elements within a basic or function block are relocated with the relocation of the basic or function block. That means we should not observe any gadget reduction for SR and CCR. However, we see reasonable (up to 40%) gadget reduction for SR and CCR. Primarily, this reduction occurs due to the dynamic code page harvesting process. Code page coverage of dynamic code harvesting process depends on how well a program or library is connected by function calls. Less connectivity of a program or library results in less code page coverage, which in turns results in less number of gadgets than the offline versions.

Some randomization tools (e.g., SR [22]) utilize some compiler optimization techniques (e.g., using leave instruction before ret instruction). A leave instruction before a ret instruction breaks a gadget (details on how leave impacts on a gadget chain in Appendix C). Through manual code inspection, we find that a substantial number of ret instructions are preceded by leave instructions in the SR’s randomized code.

Future directions. We conservatively define the upper bound of a re-randomization scheme by the time required for an attacker to achieve 100% of the Turing-complete gadget set. However, in reality, partial Turing-complete gadget set could be sufficient for an attacker in some scenarios. Thus, the relevance analysis of partial Turing-complete gadget set could be an interesting research direction.

Our findings also show that instruction-level reordering destroys almost all (∼90%) gadgets. Current gadget finding and chaining techniques no longer work when instruction reordering is enabled. Thus, redefining traditionalROPgadgets into smaller (e.g., one line) building blocks and demonstrating new gadget chain compilers (e.g., two-level construction) are interesting new attack directions. In addition, understanding the capabilities of attackers who possess a partial set of Turing-complete gadgets would be useful.

B. Impact of the Location of Pointer Leakage

RQ #2: How does the location of a code pointer leak impact the availability of gadgets in the presence of fine-grained code randomization? We measure the impact of pointer locations

| Tools  | Granularity | MIN-FP | EX-FP | Memory | Assignment | Arithmetic | Logical | Control | Function | System | Call | Preserved? |
|--------|-------------|--------|-------|--------|-----------|-----------|---------|---------|----------|--------|------|------------|
| Zipr   | Inst.       | 91.63  | 85.42 | 94.4   | 91.4      | 67.2      | 89.1    | 96.8    | 88.1     | 83.5   | 89.0 | 65.4       | 89.1 | 62.5 | 86.7 | 66.67 | 0 | ✗* |
| SR     | FB          | 23.54  | 37.91 | 25.5   | 29.3      | 19.2      | 40.4    | 31.5    | 43.1     | 48.9   | 43.2 | 47.7       | 56.1 | 36.6 | 39.9 | 22.91 | 0 | ✓ |
| MCR FF | Reg.        | 6.34   | 37.77 | 24.1   | 37.5      | 30.2      | 39.6    | 56.3    | 55.9     | 45.7   | 45.4 | 37.0       | 54.1 | 43.4 | 42.3 | 66.67 | 0 | ✓ |
| CCR BB |            | 10.89  | 33.66 | 9.7    | 26.5      | 11.1      | 46.4    | 22.6    | 35.9     | 21.9   | 39.8 | 25.9       | 45.6 | 23.2 | 44.6 | 50.0  | 0 | ✓ |

* For Zipr, TC is not preserved for minimum footprint gadgets, but TC is preserved for extended footprint gadgets.
on JIT-ROP attack capabilities, by comparing the number of gadgets harvested under different starting pointer locations. We aim to find out whether or not the number of gadgets depends on the location of a pointer leakage when a fine-grained diversification is applied. We collect the total numbers of minimum and extended footprint gadgets by leaking a random code pointer from each code page of hiawatha, httpd, lighttpd, nginx, proftpd, and thttpd.

Table IV shows the number of leak code pointers or addresses and the numbers of minimum and extended footprint gadgets that can be harvested by starting from the leaked pointers. We restrict the code harvesting process to harvest gadgets only within the text segment of an application to find how well the code of a program is connected. For all applications, we observe that the pointer’s location does not have any impact on the total number of minimum and extended footprint gadgets. For example, regardless of the location of starting point in nginx, we observe 26 minimum and 788 extended gadgets when randomized by Zipr; 222 minimum and 5277 extended footprint gadgets when randomized by SR; 111 minimum and 1731 extended footprint gadgets when randomized by MCR; and 204 minimum and 4822 extended footprint gadgets when randomized by CCR. These findings indicate that an application’s code segment is very well-connected, making JIT-ROP attacks easier.

The numbers of leaked addresses in Table IV are different for different backends. Different backends optimize the same application differently. This increases/decreases the number of code pages. Since we leak a random address from each code page, the number of leaked addresses varies for different tools.

For Zipr, we cannot pick a random code pointer from the application’s code segment, because Zipr makes the code segment sparse by transforming the segment. The sparse code segment contains many bad values. Thus, for Zipr, we randomly leak the addresses of 10 functions from each application and use those addresses as the starting points.

Future directions. Our findings imply that any valid code pointer leak from an application’s code segment is equally viable. Regardless of the randomization, a pointer leakage in any location allows attackers to access a set of minimum and extended footprint gadgets. These observations suggest that disrupting the connectivity of code segment would be an effective defense strategy. Although this kind of disruption solutions (e.g., Oxymoron [28]) exist, they increase the runtime overhead and cannot protect from the variants of JIT-ROP (e.g., Isomeron [28]). Thus, a randomization time solution that disrupts the connectivity of code while keeping the execution order intact would be an interesting research direction.

C. Impact on the Quality of a Gadget Chain

RQ #3 How does fine-grained code randomization impact the quality of a gadget chain (i.e., payload)? The purpose of this analysis is to estimate the quality of a gadget chain. We measure the quality of a gadget through the register corruption analysis for individual gadgets, following the procedure described in [IV-A].

We measure the register corruption rate for MV, LR, AM, LM, AM-LD, SM, AM-ST, SP, and CALL gadgets. Some gadgets (e.g., CP, RF, EP, etc.) described in Table VII (in Appendix) are special purpose gadgets that are used to trick defense mechanisms, such as CFI [3], kBouncer [60], and ropecker [21]. Thus, we omit these gadgets from the quality analysis.

We found that the overall register corruption rate is slightly higher (~6%) in the presence of fine-grained randomization. This slightly higher register corruption rate indicates that the formation of gadget chain is slightly harder in fine-grained randomization compare to the coarse-grained randomization.

We present the detailed results in Appendix (Table VIII). Table VIII also reports the average number of unique registers used in each gadget. This number reflects how many registers (ranging from 1 to 4) are involved in a gadget on average.

Sometimes, fine-grained randomization decreases the register corruption rate. For example, for Nginx, the corruption rate of the load memory (LM) gadgets is reduced from 44% to 15%, when fine-grained randomization is in place. This reduction is likely due to the relatively smaller number of gadgets in the presence of the fine-grained randomization.

Future directions. Most randomization solutions reorder functions, basic-blocks, and instructions. MCR [21] goes one step deeper, reorder machine registers, and replaces mov reg1, reg2 instructions with equivalent lea instruction. Besides these, designing randomization solutions that increase the register corruption rate in gadgets would be interesting as high register corruption rate would make attacks unreliable.

D. Availability of Libe Pointers

This experiment measures the risks associated with a heap, stack or data segment of an application for revealing a library

| Program | # of leaked addresses | # of MIN-FP | # of EX-FP | # of leaked addresses | # of MIN-FP | # of EX-FP | # of leaked addresses | # of MIN-FP | # of EX-FP | # of leaked addresses | # of MIN-FP | # of EX-FP |
|---------|----------------------|-------------|-------------|----------------------|-------------|-------------|----------------------|-------------|-------------|----------------------|-------------|-------------|
| hiawatha | 10                   | 9           | 223         | 42                   | 41          | 1259        | 47                   | 44          | 1042        | Zipr [28]            | 39          | 31          |
| httpd   | 10                   | 16          | 634         | 91                   | 141         | 4453        | MCR produces linking error for httpd |
| lighttpd| 10                   | 8           | 235         | 53                   | 103         | 2512        | 68                   | 118         | 2544        | 86                   | 176         | 4764        |
| nginx   | 10                   | 26          | 788         | 121                  | 222         | 5277        | 49                   | 111         | 1731        | 45                   | 74          | 1783        |
| proftpd | 10                   | 17          | 523         | 187                  | 96          | 7395        | 131                  | 115         | 4466        | 114                  | 204         | 4822        |
| thttpd  | 10                   | 8           | 172         | 17                   | 22          | 583         | 16                   | 31          | 535         | 131                  | 125         | 3986        |
TABLE V: Libc pointers in the stack, heap and data segment of a program. Stacks contain more pointers, carrying higher risks of pointer leakage.

| Program name | unique # ofschützt| unique # ofschützt| unique # ofschützt |
|--------------|------------------|------------------|------------------|
|              | pts in stack that point to libc code | pts in heap that point to libc code | pts in data segment that point to libc code |
| htiwatha     | 10               | 14               | 0                |
| httpd        | 23               | 37               | 1                |
| lighttpd     | 6                | 6                | 0                |
| mupdf        | 19               | 40               | 2                |
| nginx        | 10               | 12               | 0                |
| openssl      | 19               | 41               | 2                |
| proftpd      | 23               | 36               | 1                |
| sqlite3      | 19               | 41               | 2                |
| ssh          | 19               | 26               | 0                |
| thttpd       | 17               | 20               | 2                |
| tor          | 18               | 66               | 1                |

Average 17 31 1 3 1 1

E. Impact of the Compiler Optimizations

To assess the impact of code transformations and optimizations, we attempt to discover what kind of code optimizations and transformations can impact the availability of various types of gadgets. To do this, we prepare normal and randomized binaries with different optimization levels (-O0, -O1, -O2, -O3, -Ofast, -Os). We select three server applications (nginx, apache, proftpd), one secure networking utility application (openssh), and one lightweight database (sqlite3) to assess the impact of code optimizations.

The interesting finding is that the unoptimized code seems to be more secure than optimized code. Figure 5 shows the number of Turing-complete gadgets in different optimization levels. On average, the optimization levels greater than or equal to -O1 have 72 more gadgets than -O0 for GCC and 75 for Clang (not shown in the Figure 5 for brevity). We analyze and find the following reasons.

Reason 1: The main reason for the unoptimized code (-O0) to have such a low number of gadgets is that the unoptimized code has zero (0) LM, SM, and MR gadgets for all applications. All three gadgets (LM, SM, and MR) are involved with the mov instruction. In unoptimized code, other instructions such as leave, pop rbp, add rsp, 0x30, etc. are present between the mov and ret instructions. However, optimized code (≥ -O1) may remove these additional instructions between mov and ret. Listing 2 shows portion of assembly code in three optimization levels (-O0, -O1, and -O2) for the C function demonstrated in Listing 1. Listing 2 shows that there is no mov and ret instructions stay together in optimization level -O0 or -O1, but in optimization level -O2. The tendency of mov and ret instructions staying together in optimized code primarily contributes to the presence of LM, SM, and MR gadgets in optimized code.

Listing 1: Sample C function.
```c
long f(int i){
    if (i==0) return 1;
    else return i * f(i-1);
}
```

Listing 2: Portion of assembly code of the C function above in different optimization levels.

| Optimization Level | Assembly Code |
|--------------------|---------------|
| -O0                | mov edi, eax  |
|                    | add rsp, 0x18 |
|                    | pop rbx       |
|                    | ret           |
| -O1                | mov ebx, edi  |
|                    | mov rbx       |
|                    | pop ret       |
| -O2                | mov eax, 0x1  |

Reason 2: For optimizations, compilers sometimes emit extra instructions that increase gadgets. Additionally, many mov instructions get replaced by xor instructions. This replacement increases logical gadgets while decreases MR gadgets.

VI. DISCUSSION

Metrics for evaluating fine-grained randomization. Traditionally, both coarse- and fine-grained randomization solutions use entropy to measure the effectiveness of hindering code-reuse attacks [22, 46, 81, 84]. Randomization tools such as
PaX ASLR [31], SR [22], CCR [46], Remix [20]. Binary stirring [34], ILR [40] and ASLP [45] use the entropy values as the security metrics to evaluate the security of their randomization schemes. Some tools such as SR [22], CCR [46], Remix [20], and ASLP [45] calculate the entropy value as a function of the number of functions and basic blocks. That means these tools permute the order of functions or basic blocks of program code and place it different places in the address of that program. These tools also consider some constraints such as executable size, and fall-through basic blocks.

However, such an entropy measure is not useful under the JIT-ROP threat model, as chunks of code are still available. Including distances between permuted functions or basic blocks in the entropy computation would not work either, because the code’s semantic connectivity (e.g., through jump and call) is still not captured. Code connectivity is what JIT-ROP attacks leverage to discover code pages. In comparison, our measurement methodology more accurately reflects JIT-ROP capabilities and is more meaningful under the JIT-ROP model. How to design an entropy-like metric to capture the degree of code isolation or the semantic connectivity in code is an interesting open problem.

**Availability of Block-Oriented Programming (BOP) gadgets.** A BOP attack chains blocks of code (e.g., basic blocks) to achieve malicious goals [43]. We attempted to evaluate the impact of code randomization on the availability of BOP gadgets [43]. We used the BOP compiler (BOPC) to find the BOP gadgets. For CCR [46] and MCR [41], we observed almost an identical number of BOP functional blocks for register assignments, register modifications, memory reads, memory writes, system/library calls and conditional jumps in the randomized versions compared to the non-randomized version. The identical number is expected as CCR and MCR reorder the basic or functional blocks without reordering the content of a basic block or a functional block. This implies that randomization solutions up to basic block-level have no impact on the availability of BOP gadgets.

**Reachability of gadgets.** We design our experiments based on the availability of various kinds of gadgets. However, in reality, it is not an easy task to invoke the available gadgets. Attackers need to conduct a series of operations including finding a vulnerability or leaking memory for the actual invocations of gadgets. In Section II we assume that an attacker has already overcome the initial obstacles, especially finding a memory leak. Our experiments are focused on the available gadgets utilizing the leaked memory to compare various code (re-)randomization techniques.

**Operational re-randomization intervals.** Our methodology helps guide software owners (e.g., server owners) to set the appropriate re-randomization intervals. For example, if the owners prioritize the performance over security, then they can set re-randomization time as the time just before when the gadget discovery process achieves 100% of the Turing-complete gadgets. If the owners prioritize security over performance, they can consider setting the interval as the time when the gadget discovery process achieves around 60-70% of the Turing-complete gadgets.

**Need for randomizing Glibc.** Unfortunately, SR, CCR, MCR, and Zipr were all unable to completely randomize the Glibc implementation. For CCR and MCR, the LLVM Clang compiler (which CCR and MCR use as their compilers) does not have the support for certain GCC specific extensions in Glibc. Glibc contains GCC specific non-standard extensions (e.g., ASM GOTO), which Clang does not cover. SR cannot randomize some parts of Glibc. Therefore, we evaluate a lightweight version of the standard C library musl-libc [1] instead of Glibc. Selfrando works on musl-libc. However, we are unable to diversify it with the other tools. On the other hand, shuffler can reorder Glibc code by making a few modifications such as disabling manual jump table construction.

**Limitations.** Our current work does not measure zombie gadgets [76]. The gadgets that are available after applying destructive read defenses are called zombie gadgets [76]. Destructive read defenses (e.g., XnR [6], NEAR [65], Readactor [24], and Heisenbyte [80]) are known to protect programs from JIT-ROP attacks. Destructive read defenses only allow code execution. Any attempt to read code pages terminate a process. In this way, destructive reads destroy the availability of gadgets to attackers. However, destructive read defenses cannot completely eliminate all gadgets. For example, runtime code generation capability of JIT compilers allows the creation of multiple copies of the same code (e.g., two native code regions can be created from the same JavaScript code, one copy is used for disclosing layout, and another copy is used for mounting attacks). In addition, loading and unloading features of dynamic libraries allow attackers to load, disclose, destroy, and unload code pages. A fresh loading of the destroyed code pages can be used in attacks utilizing the layout information of the disclosed code pages. Similarly, attackers can infer code layout by creating new processes (e.g., creating new tabs in browsers using JavaScript) and making an informed guess about neighboring bytes after disclosing a few bytes (i.e., implicit reads [76]). Thus, JIT compilers, load/unload features, new process creation, and implicit reads allow attackers to get gadgets even in the presence of destructive read defenses.

In our future work, we plan to assess the availability of zombie gadgets after applying many destructive read defenses. In particular, we plan to assess the entity (i.e., JIT compilers or load/unload feature or new process creation or implicit reads) that can facilitate attacks by providing most gadgets. We will categorize the available zombie gadgets in seven Turing-complete (TC) categories and measure the availability of zombie gadgets in different TC categories.
Another limitation is that our threat model assumes that code-pointer-obfuscation based defense is not deployed. If used, code pointer obfuscation could make JIT-ROP code page discovery less effective, reducing the gadget availability. For example, Oxymoron [7] showed some effectiveness for obstructing a JIT-ROP attack by making code pointer transformation or redirection through a randomization-agnostic translation table. Code Pointer Integrity (CPI) proposed by Kuznetsov et al. [43] is shown to be effective for mitigating JIT-ROP and COOP attacks. Understanding how code pointer obfuscation impacts JIT-ROP and measuring the effectiveness of these defenses under various attack conditions (e.g., Isomeron [29] and COOP [68]) are interesting problems.

Key Takeaways

Effective re-randomization interval. A methodology for the systematic measurement of a Turing-complete gadget set can help compute the effective upper bound for re-randomization intervals of a re-randomization scheme. Our experiments show that this upper bound ranges from 4 seconds to 17 seconds for various applications with dynamic libraries. The upper bound indicates the maximum amount of time between two consecutive randomization rounds that prevent an attacker from obtaining a Turing-complete gadget set. Applying our methodology on their own machines will help re-randomization adopters to make more informed configuration decisions.

Turing-complete operations. Function, basic-block, or machine register level fine-grained randomization preserves Turing completeness, however, instruction-level randomization does not. Besides, unoptimized code seems to limit more Turing-complete operations than optimized code.

All leaked pointers are created equal. Regardless of the location of pointer leakage, we are able to obtain the same number of minimum and extended footprint gadgets via JIT-ROP. This observation indicates that any pointer leak from an application’s code segment is equally useful for attackers. Any leaked pointers would enable attackers to harvest a large number of code pages and gadgets.

Connectivity. Code connectivity is the main enabler of JIT-ROP. As the conventional entropy metric does not capture code connectivity, it should not be used to measure ASLR security under the JIT-ROP threat model. Approaches for obfuscating code connectivity are promising in building JIT-ROP defenses.

Gadget quality. Our findings suggest that the current fine-grained randomization solutions do not impose significant gadget corruption.

VII. RELATED WORK

The research conducted in the system security area primarily has two themes: 1) demonstrating attacks and 2) discovering countermeasures. Attack demonstrations range from stack smashing [59], return-to-libc [47, 55, 63, 87], to ROP [15, 16, 44]. Jump Oriented Programming (JOP) [12], DOP [42], ASLR bypasses [10, 28, 33, 42, 73], and CFI bypasses [9, 14, 15, 86, 43]. In the meantime, researchers have proposed a range of defenses for ROP attacks [3, 11, 17, 21, 24, 25, 27, 29, 30, 32, 37, 56, 58, 60, 61, 62, 69, 82, 83, 89], CFI bypass [88], and ASLR bypass [6, 71, 8, 20, 24, 28, 35, 40, 45, 49, 51, 52, 61, 80, 84, 85, 86]. A categorical representation of these defenses is given in our attack-path diagram (Figure 6 in the Appendix). Binary analysis tools are also available to understand [74] and mitigate [83] these ROP or code-reuse attacks.

### TABLE VI: Conditions and capabilities of offensive techniques.

| Attack | Need a leak | CG ASLR w/o PIE | CG ASLR w/ PIE | FG ASLR | FG Tools | CFI | FG Tools |
|--------|-------------|----------------|---------------|---------|----------|-----|----------|
| AOCR   | [66]        | ✓             | ✓             | ✓       | ×        | Reader² | 24     |
| JIT-ROP | [74]        | Yes           | ✓             | ✓       | ×        | ORP  | 61      |
| BOP    | [10]        | Yes           | ✓             | ✓       | ×        | ⊕    | ×        |
| DOP    | [42]        | Yes           | ✓             | ×       | ×        | ⊕    | ×        |
| CROP   | [33]        | No            | No            | ✓       | ×        | *    |         |
| BRO   P  | [10]        | Yes           | ✓             | ✓       | ⊕        | Oxymoron | 7      |
| CFI    | [15]        | Yes           | ✓             | ✓       | X        | ⊕    | Oyymoron |
| OOC    | [52]        | Yes           | ✓             | ✓       | ⊕        | ~    |         |
| EHH    | [19]        | Yes           | ✓             | ✓       | ⊕        | ⊕    |         |

Most of the above-mentioned defenses are variants of W⊕X (e.g., No-Execute-After Read [65] and Heisenbyte [80]), memory safety (e.g., HardScope [57], Memcheck [54], AddressSanitizer [71], and StackArmor [19]), ASLR (e.g., fine-grained code randomization/code diversification [20, 46, 84], code re-randomization [8], [86], and SGX-Shield [79]), and CFI (e.g., CCFIR [88] and bin-CFI [89]). These defenses are capable of preventing most code-reuse or ROP-based attacks [10, 28, 33, 73] except a few cases such as inference attacks that are performed using zombie gadgets [76] or relative address space layout [66]. However, in practice, imprecision in resolving indirect control-flow transfers impacts CFI’s security guarantees. In addition, there are trade-offs between using coarse-grained CFI (performance overhead is low when enforced) and precise CFI (performance overhead is high when enforced). Similarly, some attacks (e.g., DOP [42]) fail in the presence of a position independent executable. Table VII shows some attacks that bypass many of the modern defenses. We infer this information from the papers. Some information is not explicitly mentioned in those papers. We indicated these by — and *. Our work, quantitatively measuring to what extent ASLR makes code-reuse attacks difficult, complements these attack demonstrations and defenses. Shacham et al. measured the entropy improvement (at most 1 bit compared to PaX ASLR [51]) by doing function-level reordering in their paper [73]. That work did not measure how the function-level reordering impacts ROP gadgets. We evaluate the impact of function-level randomization as well as the basic block level randomization. Besides, Veen et al. demonstrated a dynamic gadget discovery tool called NEWTON that assists attackers for crafting code-reuse exploits [82]. However, they do not perform quantitative analysis like ours.
VIII. Conclusions

We presented multiple general methodologies for quantitatively measuring the ASLR security under the JIT-ROP threat model and conducted a comprehensive measurement study. One method is for computing the number of various types of gadgets and their quality. Another method is for experimentally determining the upper bound of re-randomization intervals. The upper bound helps guide re-randomization adopters to make more informed configuration decisions.

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APPENDIX

A. Register corruption analysis

Typically, a gadget contains a core instruction (other than ret) that serves the purpose of that gadget. For example, the core instruction of the gadget in Listing 3 is mov eax, edx and the gadget serves as a move register (MR) gadget. The core instruction is the instruction that an attacker needs. All the instructions (except ret) before/after the core instruction is unnecessary. However, these additional instructions may modify the source/destination register value of a core instruction. If these additional instructions modify the register values of a core instruction, we treat the gadget as a corrupted gadget. In Listing 3 the instruction (mov edx, DWORD PTR [rdi]) before the core instruction modifies the value of the source register (edx) of the core instruction and the instructions (shr eax, 0x10; xor eax, edx) after the core instruction modify the destination register (eax) value. We identify three scenarios when core instructions get corrupted as follows:

1) **Scenario 1**: A core instruction is only affected by the instruction(s) before the core instruction,

2) **Scenario 2**: A core instruction is only affected by the instruction(s) after the core instruction, and

3) **Scenario 3**: A core instruction is affected by both the instruction(s) before/after the core instruction.

For each gadget, we consider these three scenarios and determine whether the gadget is corrupted or not.

Listing 3: An example gadget where the core instruction is “mov eax, edx;”.

```
mov edx, DWORD PTR [rdi]; mov eax, edx; shr eax, 0x10; xor eax, edx; ret;
```

Considering the three scenarios above, we identify three types of gadgets where the core instruction can get corrupted. Figure 7 shows the three type of gadgets. Each gadget has one or more instructions before or after the core instruction. For example, Type 1 gadget in Figure 7 has a core instruction in the middle and one or more instructions before or after the core instruction. The core instruction has two registers for this kind. One or more instruction(s) before the core instruction may modify the source register (rdx) in Figure 7a Similarly, one or more instruction(s) after the core instruction may modify the destination register (rax) in the figure.

However, for Type 2 gadget in Figure 7b the core instruction has just one register. That means that the additional instructions before the core instruction cannot affect the register of the core instruction. Thus, we do not care the instructions before the core instruction. For Type 3 gadget in Figure 7c the core instruction write the value of rdi to a memory location pointed by rax. That is why we do not care if the register (rax, rdi) values get modified by the instructions after the core instructions.

We treat a gadget as corrupted if registers in the core instruction get modified. We perform our register corruption analysis by identifying the corrupted registers in the core instructions of a gadget as follows.

First, we identify the set of instructions (before/after the core instruction) that can modify the source/destination register of the core instruction. We find that 17 instructions (mov, lea, add, sub, imul, idiv, pop, inc, dec, xchg, and, or, xor, not, neg, shl, and shr) can modify a register value of a core instruction. That means that these instructions use the source register of a core instruction as its destination register or the destination register of a core instruction as its source register. We treat the registers of such instructions as conflicting registers.

Second, we extract the conflicting registers for Type 1 and 3 gadgets. We call this set of registers as RegSet1. Similarly, we extract RegSet2 for the instructions after a core instruction for Type 1 and 2.

Third, if the RegSet1 and/or RegSet2 contain more than one conflicting registers, we treat the core instruction of that gadget as corrupted, i.e., the gadget itself is corrupted.

In this way, We measure the register corruption rate for MV, LR, AM, LM, AM–LD, SM, AM–ST, SP, and CALL gadgets.

B. Validation of randomization results

We evaluate the randomization tools, i.e., Zipr [38], SR [22], MCR [41], and CCR [46] using the common set of applications and libraries that the four randomization tools can randomize. Figure 8 shows the reduction of Turing-complete gadgets observed for different randomization tools using the common set of applications and libraries. In most cases, the reduction using a different set of applications and libraries is similar to the reduction using a common set of applications.
C. Impact of leave Instruction

Intuitively, one might think that a leave instruction may provide similar functionality to an LR gadget, as it unfolds to \texttt{mov rsp, rbp; pop rbp}. Or, a store memory (SM) gadget might still serve its purpose with the addition of a leave instruction once unfolded. However, the leave instruction modifies the stack pointer (SP), which affects the control flow of the resulting gadget chain. We experimentally prove the impact of leave instruction on a gadget chain in the following paragraph.

If we unfold the leave instruction, we get two instructions: \texttt{mov rsp, rbp} and \texttt{pop rbp} in Intel syntax. Every time when a function returns, it resets the stack pointer (\texttt{rsp}) by the value of the base pointer (\texttt{rbp}) using \texttt{mov rsp, rbp} instruction, restores the old \texttt{rbp} value from the stack using \texttt{pop rbp} instruction, and calls \texttt{ret} instruction. Compiler optimization techniques replace the \texttt{mov} and \texttt{pop} instructions by a single leave instruction. This reduces the overall program size. When the leave instruction is used, a function simply returns by using the leave instruction followed by a \texttt{ret} instruction. Since leave instruction resets \texttt{rsp} to \texttt{rbp}, this redirects the control-flow of a gadget chain if the leave instruction is used in the gadget chain. To assess the impact, we write two ROP gadget chains that spawn a shell. One of the gadgets of the first chain is \texttt{mov rax, 0x1; ret}.

Fig. 6: High-level view of the types of ROP attacks and attack-paths based on various security measures. Each rectangle and circle indicates security measures and attack types, respectively. AC stands for attack condition. All the attack conditions have W⊕X, PIE, Canary, and RELRO implicitly.

![Fig. 6: High-level view of the types of ROP attacks and attack-paths based on various security measures.](image)

![Fig. 7: A set of gadget types for measuring the quality of individual gadget through the register corruption analysis.](image)

![Fig. 8: Reduction (%) of Turing-complete gadgets observed for different randomization tools using the common set of applications and libraries that the randomization tools can randomize.](image)
TABLE VII: Gadgets used in advanced ROP attacks [10, 14, 15, 36, 75]. △ indicates an addition/subtraction/multiply/division. ▽ indicates any operation that modifies stack pointer (SP). SN → Short name. TC? indicates whether a gadget is included in the Turing-complete gadget set or not.

| Gadget types        | Purpose                                      | Minimum footprint         | Example               | TC? | SN  | Source |
|---------------------|----------------------------------------------|---------------------------|-----------------------|-----|-----|--------|
| Move register       | Sets the value of one register by another    | mov reg1, reg2; ret       | mov rdi, rax; ret     | ✓   | MR  | [75]   |
| Load register       | Loads a constant value to a register         | reg1, reg2; ret           | pop rbx; ret          | ✓   | LR  | [14], [75] |
| Arithmetic          | Stores an arithmetic operation's result of   | add rcx, rbx; ret         | add rsi, [rbp]; ret   | ✓   | AM-LD| [75]   |
| Load memory         | two register values to the first             |                            |                       |     |     |        |
| Arithmetic load     | △ a memory content to/from/by a register and | reg1, [reg2]; ret         | mov rax, [rdx]; ret   | ✓   | LM  | [14], [75] |
| Store memory        | in store that register                      |                            |                       |     |     |        |
| Arithmetic store    | △ a register value to/from/to a memory       | sub [ebx], eax; ret       | sub [ebx], eax; ret   | ✓   | AM-ST| [75]   |
| Stack pivot         | content and stores in that memory           |                            |                       |     |     |        |
| Jump                | Sets the stack pointer, SP                  | xchg rsp, rax             |                       |     | SP  | [75]   |
| Call                | Jumps to a function through a register or   | syscall or int 0x80; ret  | syscall               | ✓   | SYS | [65]   |
| System Call         | or indirect call                             |                            |                       |     |     |        |
| Call preceded       | Bypasses call-ret ROP defense policy         | mov [reg1], reg2;         | mov [rsp], rsi;       |     |     |        |
| Context switch      | Allows processes to write to Last Branch    | long loop                 | 3dd4: dec, ecx        |     |     |        |
|                    | Record (LBR) to flash it                     |                            | 3dd5: fmul, [BC8h]    |     |     |        |
| Flashing            | Clears the history of LBR                   | Any simple call           | jmp A                 |     |     |        |
|                    | (Last Branch Record)                        | preceeded gadgets with    | ...                   |     |     |        |
|                    | a ret instruction                           | a ret instruction         | ...                   |     |     |        |
|                    |                                              | A: mov rax, 3; ret;       |                       |     |     |        |
| Terminal            | Bypasses kBouncer heuristics                | Any gadgets that are      | N/A                   |     |     |        |
|                    |                                              | 20 instructions long      |                       |     |     |        |
| Reflector           | Allows to jump to both call-preceded or     | mov [reg1], reg2;         | mov [rsp], rsi;       |     |     |        |
|                    | non-call-preceded gadgets                   | call reg3; ... ; jmp reg4| call rdi; ... ; jmp    |     |     |        |
|                    | This gadget chains the control to go        | call reg or call [reg];  | call rdi;             |     |     |        |
|                    | forward when we have the control            | ...                      | ...                   |     |     |        |
|                    | on the stack and ret                        | ret;                     | ret                   |     |     |        |
| Entry point         | This gadget chains the control to go        | pop rbp;                 | pop rbp               |     |     |        |
|                    | forward when we have the control            | ... call/jmp reg or      | ... call/jmp reg or   |     |     |        |
|                    | of a call instruction                       | call/jmp [reg]           | call/jmp [reg]        |     |     |        |
| BROp                | Restores all saved registers                | pop rdx; pop rbp;        | pop rdx; pop rbp;     |     |     |        |
|                    |                                              | pop r12; pop r13;         | pop r12; pop r13;     |     |     |        |
|                    |                                              | pop r14; pop rsi;        | pop r14; pop rsi;     |     |     |        |
|                    |                                              | pop r15; pop rdi;        | pop r15; pop rdi;     |     |     |        |
|                    |                                              | ret;                     | ret;                  |     |     |        |
| Stop                | Halts the program execution                 | Infinite loop            | 4a833dd4: inc rax     |     |     |        |

TABLE VIII: Register corruption for various gadgets. The numbers before and after the vertical bar (|) represent the average number of unique register usage and register corruption rate in a gadget, respectively. CG → Coarse-grained. FG → Fine-grained. Fine-grained versions prepared using SR [22].

| Program | MV | LR | AM | AM-LD | SM | AM-ST | SP | CALL | Average |
|---------|----|----|----|-------|----|-------|----|------|---------|
| Nginx   | 4  | 11%| 2  | 0.3%  | 2  | 0.3%  | 2  | 0.3% | 16.3%   |
| Apache  | 4  | 16%| 2  | 0.5%  | 3  | 0.7%  | 2  | 0.3% | 16.3%   |
| ProFTPD | 3  | 69%| 2  | 0.6%  | 3  | 0.7%  | 2  | 0.3% | 16.3%   |

Average: 31.5%
mov rax, 0x1; leave; ret to generate a second gadget chain. So, the gadget chains are as follows: <...clipped...> mov rax, 0x1; ret <...clipped...> and <...clipped...> mov rax, 0x1; leave; ret <...clipped...>. We successfully get a shell using the first gadget chain but fail to get a shell using the second chain. The reason for the failure is that the rsp is reset to rbp which results in the redirection of the execution of gadget chain from the address (or value) saved in rbp. In this way, leave instructions break the gadget chain.